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MINERALOGY OF THREE SULPHATE DEPOSITS OF NORTHERN CHILE*

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ABSTRACT

This paper gives the results of a study of the mineralogy of Chuquicamata, Quetena, and Alcaparrosa, three sulphate deposits near Calama, in Northern Chile. The sulphate and chloride minerals, their description, their paragenesis, and the geochemistry of their formation, are the primary interest of the paper. The minerals described were collected by the author in 1935.

Seventy-six minerals were identified and studied. Eighteen of these minerals are known only from northern Chile and twelve are known only from these three deposits. An attempt has been made to clear up some of the varietal names and doubtful species that have been described from these mines. Seven new well-defined mineral species were discovered during the research—antofagastite, bandylite, leightonite, ungemachite, and lindgrenite have been described elsewhere; metasideronatrite and parabutlerite are described here. For all of these, complete crystallographic, optical, and chemical data were secured. Important new crystallographic data are presented for the minerals szomolnokite, pickeringite, rhomboclase, botryogen, lapparentite and natrojarosite. New *x*-ray data were obtained on three minerals and new optical data on sixteen, and nine new chemical analyses are presented.

PART I. GEOLOGY AND PARAGENESIS

INTRODUCTION

A detailed study of the mineralogy of Chuquicamata, Quetena and Alcaparrosa in Northern Chile forms the basis of this paper. The writer worked for five years at Chuquicamata and had ample opportunity to study the deposits in the field. In 1935 he returned to Chile in behalf of Harvard University and the United States National Museum and spent four months collecting minerals throughout northern and central Chile. Extensive suites of specimens were collected from these three deposits and later were studied in the laboratories of Harvard University and the United States National Museum. The sulphate minerals of these deposits are the primary interest of this paper.

The writer wishes to acknowledge the financial assistance given him by the Department of Mineralogy, Harvard University, and the United States National Museum, which made this study possible. He received unstinted aid and advice from Professor Charles Palache, Dr. W. F. Foshag, Mr. E. F. Henderson and Dr. M. A. Peacock, and it is a pleasure to acknowledge this. The writer wishes to mention particularly the aid given by Dr. Harry Berman, whose guidance and unfailing interest in this study contributed in great part to its present form and value.

Geography. Northern Chile is usually divided into three broad topographic and geographic divisions—the Coast Range, the Central Valley and the Cordillera Real. The Coast Range rises abruptly from the Pacific Ocean on the west and reaches elevations of over 1,500 meters. The Central Valley to the east of the Coast Range is a relatively shallow and broad valley from 50 to 100 kilometers wide. The western slopes of

the Cordillera Real form the eastern side of the Central Valley. This great chain of volcanic peaks marks the eastern boundary of Chile.

The deposits of Chuquicamata, Quetena, and Alcaparrosa (Fig. 1) lie near latitude 22° south, longitude 69° west, in the Province of Antofagasta, at elevations ranging from 7,000 to 10,000 feet. They are reached from Antofagasta by train (150 miles) or from Tocopilla by road (90

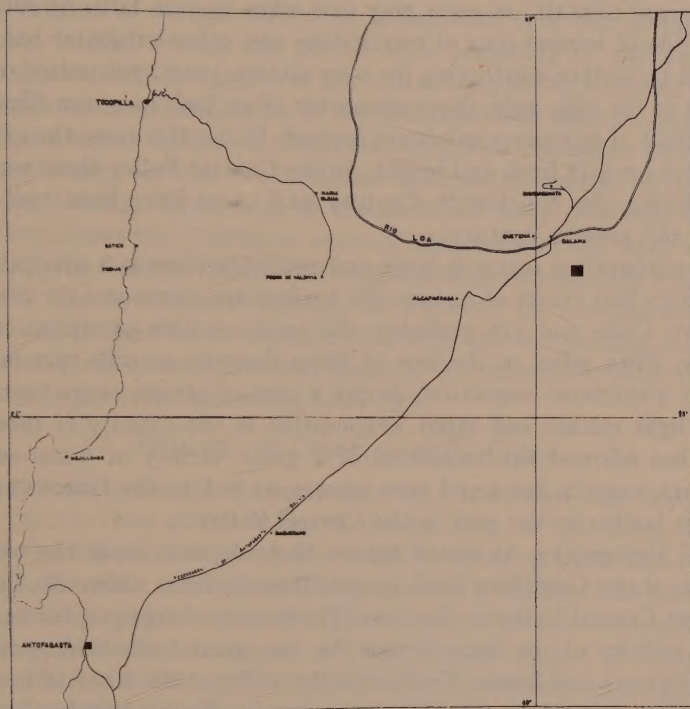


FIG. 1. Key Map of Northern Chile showing relative locations of Chuquicamata, Quetena and Alcaparrosa Mines.

miles). Both of these cities are on the coast. The only other city of any size in the Province is Calama, a small city about equidistant from the three deposits. All these deposits are reached by auto roads from Calama; Chuquicamata 12 miles to the north, Quetena 5 miles to the west, and Alcaparrosa 18 miles to the south.

The deposits lie in the northeast portion of the Atacama Desert on the west slopes of the Cordillera Real, 100 miles west of the crest of this range.

Climate. Northern Chile, particularly the Atacama Desert, is probably one of the driest areas on the earth. These deposits, on the edge of the desert, receive an hour or so of light rain once or possibly twice a year. The average rainfall varies slightly in the three deposits; Chuquicamata, the highest and farthest to the east, receives the greatest annual amount, less than 5 mm.; and Alcaparrosa, the lowest and the one farthest to the west, has a fall of about 1 mm. a year. There is really no "average rainfall" as years may pass when no rain falls. At Alcaparrosa a pile of several tons of coquimbite and other sulphates has been exposed to surface weathering for over sixteen years, yet today, on the outside of the pile, only about a quarter of an inch has been dissolved and a crust of secondary sulphates formed. Under this crust the original sulphates are still fresh and bright. In the Central Valley there were six rains during the Nineteenth Century and there have been two rains during the present century.

The evaporation factor is large and probably there is a precipitation deficiency. Salt crusts at or near the surface are common over much of northern Chile and are probably the result of this precipitation deficiency. Fifty miles to the east of these deposits enough rain falls to support a scattered vegetation during a part of almost every year.

The light rainfall and rapid evaporation in the vicinity of these deposits has allowed the formation of a great variety of water-soluble sulphates, some in large and pure masses, as well as the famous nitrate deposits farther to the west in the Central Valley.

Local Topography. As stated before, these deposits lie in the western foothills of the Cordillera Real, several thousand feet above the floor of the great Central Valley to the west. The dominant topographic features in the vicinity of the deposits are the two great batholithic peaks of Chuquicamata and Limon Verde with the valley of the Rio Loa between them. The deposit at Chuquicamata lies in the batholith, near the eastern edge. Alcaparrosa lies to the west of the Limon Verde batholith. The area is one of mature topography as a whole. The hills have moderate to steep slopes and narrow ridges with alluvium-covered lower reaches. Undrained basins are common, usually occupied by salt plains or salars. Remnants of old salars that have been tapped by tributaries of the Rio Loa are uncommon but can be found.

Geomorphology. Volcanism probably began in Northern Chile in the late Triassic. Following this volcanism there was a slow subsidence and a long period of sedimentation, first of the playa-lake type and then in shallow inland seas during the Jurassic and early Cretaceous. During the Cretaceous, the sea retreated and at the close of the Mesozoic or beginning of the Tertiary folding began and this ushered in the present

cycle. Accompanying the folding was strong volcanism and batholithic intrusion on a grand scale.

The coast range, which follows the present coast line of northern Chile, was probably formed at the close of the Cretaceous. At the beginning of the Pliocene when the general uplift of the Andes began, the Cordillera to the east was raised to its present heights and the coast range was certainly elevated several thousand feet. The Central Valley of Chile, which consists of several valleys or basins with very low divides, was probably formed during this period. The beginning of the period of uplift was marked by erosion of the older rocks under semi-arid conditions with torrential deposition of the debris in thick beds of conglomerates in the broad valleys. Contemporaneous with the uplift, active volcanism was renewed and has continued down to the present, but is probably diminishing. Thick beds of andesitic ash were deposited at this time throughout the Cordillera; some of this material was later washed down into the Central Valley. The conglomerates and ash beds deposited from the middle Tertiary through the Pliocene are now subjected to erosion and in these beds the present drainage has cut youthful canyons. The present arid climate probably began in the Pliocene or early Pleistocene and is probably increasing in aridity.

GEOLOGY OF CHUQUICAMATA, CHILE

Chuquicamata lies on the west slope of a low ridge that disappears under the alluvium of the valley of the Rio Loa, to the south. To the west of the deposit, across a broad shallow valley, is a hill about 1,300 feet high, the main mass of the Chuquicamata batholith. This batholith has an areal extent of about 80 square miles with a north-south axis. The Chuquicamata ore deposit is roughly pear shaped in horizontal section with the wider portion to the north. Its dimensions are approximately 2 miles by 0.7 mile.

History. The first mining in the vicinity was carried on by the aborigines on the gold deposit at the north of the present mine. Recent efforts to find gold, even in traces or colors in this area, have been fruitless. The copper veins were also worked by the aborigines and may have been exploited by the Spaniards. Foreign capital came into the district about 1879 and active mining of the veins on the eastern edge of the deposit continued until about 1920. In 1915 active open-pit mining on a large scale with steam shovels began.

Outline of Geologic History. The geology of the Chuquicamata deposit has been described by Taylor¹ and only a brief outline will be given here:

¹ Taylor: Copper Resources of the World, *16th Int. Geol. Cong.*, vol. II, pp. 473-484, 1935.

1. Intrusion of the granodiorite batholith into the Jurassic shales, probably at the close of the Mesozoic.

2. Fracturing along a fissure on the west side of the deposit followed by the flow of solutions along this fracture and the alteration of the granodiorite to the east of the fracture. Orthoclase and perthite phenocrysts formed in the granodiorite, replacing the salic minerals and possibly some of the femic minerals, although fresh biotite occurs as inclusions in the phenocrysts.

3. Fracturing within the area of the present ore body followed by heavy silicification along the major fractures. With the silicification, hematite and magnetite may have been introduced to the east of the deposit, while pyrite, chalcopyrite, bornite, and molybdenite were introduced into the central and northwest portions. To the northwest these minerals were introduced with a carbonate gangue. Gold may have been introduced at this time in an area of intense silicification to the north.

4. Accompanying and following the silicification there was sericitization of the granodiorite along the central fissures, decreasing in intensity to the east and west, being most intense between the central and west fissures. Orthoclase phenocrysts were not sericitized except in areas near the fissures.

5. Probably a renewal of crushing and shearing along the principal fissures followed by the main period of copper mineralization, namely, pyrite, enargite, and covellite. During this period the veins along the northeast side formed.

6. A period of oxidation and leaching during the middle Tertiary with secondary enrichment and the development of a leached capping over the deposit. The erosion of the iron veins to the east resulted in the formation of iron conglomerates or itabirite.

7. Pliocene uplift with the introduction of an arid climate. Slight movements in the deposit developed flat, rolling fractures.

8. Erosion and oxidation from the Pliocene to the present. A fluctuating water table with very limited rainfall has resulted in the dissemination of the enriched zones formed during the previous stage. The many iron and copper sulphates and other supergene oxide minerals were formed at this time.

GEOLOGY OF QUETENA, CHILE

The Quetena deposit lies to the west of Calama, Chile, near the crest of a steep hill that strikes about north-south. The ridge terminates abruptly at the Rio Salvador, and at its highest point it is about 1,300 feet above the level of the river. It receives about the same amount of rain as Chuquicamata. The deposit was mined for its oxidized copper

ores by an open pit, measuring about 125 feet by 40 feet by 25 feet deep (Fig. 2); notwithstanding this small extent, it exhibits a highly complex mineral assemblage shown in Table I B. It is the type locality for two new mineral species, antofagastite and bandylite; five mineral varieties, quetenite, salvadorite, rubrite, kubeite, and cuprocopiapite, as well as type crystals of pickeringite and co-type crystals of halotrichite.

This deposit is also referred to in older literature as Mina Salvadora.

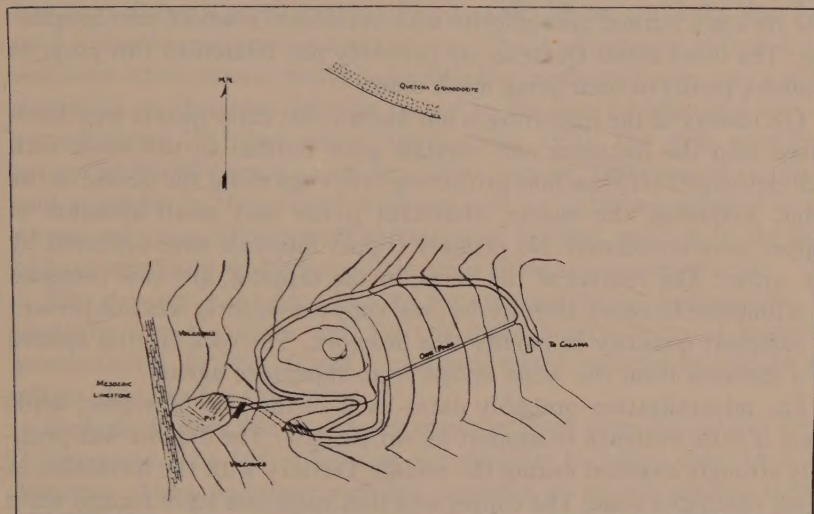


FIG. 2. Sketch Map of Mina Quetena, Chile. Scale 1 inch = .3 mile.
Contour interval—25 ft.

History. A few prospect pits were sunk on the deposit before 1890 but the actual mining records are not available today. Minerals from the deposit appeared in descriptions in Germany about 1890. It was well known that a small tonnage of low-grade ore existed there, but it was not until about 1916 that it was actively worked. Mr. Green obtained the property and transported the ore to the banks of the Rio Salvador, where a small leaching plant was erected. Mining was carried on for several years, after which the property was abandoned due to the decline in the price of copper after the World War. In 1935 an unsuccessful attempt was made to operate the property. The estimated total production of the property is about 10,000 tons, and the present positive reserve of low-grade ore is about 10 tons.

Structure. Quetena occupies a stockwork of quartz veins in a series of lava flows or possibly intrusives at the contact with a series of Jurassic

(Bajocian) cherty limestones. The stockwork is irregular in shape, a type of structure called "rebosadero" by the Chilean miners. The quartz veins vary in width up to ten inches or more. The history of the fracturing is not known and no age can be definitely ascribed to either the flows or the mineralization.

Geologic History. About a half mile to the north of Quetena, an igneous plug of red granodiorite forms the hill known as Cerro Quetena. This plug is probably connected genetically with the Limon Verde batholith. The rock is a normal granodiorite with occasional areas of micropegmatite. The flows about Quetena are probably not related to this plug, as evidence points to their being much older.

The history of the fracturing is not known, but early quartz was introduced into the fractures and crystals grew normal to the walls with well-developed terminations projecting into vugs along the course of the veins. Following the quartz, abundant pyrite and small amounts of copper were introduced. No primary copper minerals were observed by the writer. The centers of the veins, in the capping, are now occupied by a limonite boxwork after pyrite, and copper evidently was not present in sufficient quantity to modify this boxwork. The rock is little altered at a distance from the veins except from supergene agents.

The mineralization probably dates back to the late Mesozoic, while there is little evidence to support an earlier date. The deposit was probably strongly oxidized during the middle Tertiary with the formation of a rich chalcocite zone. The copper and iron sulphates have formed since the Pliocene. Undoubtedly a considerable amount of leached capping has been eroded from the deposit.

A discussion of the geochemistry of the deposit is given under the section on Paragenesis.

GEOLOGY OF ALCAPARROSA, CHILE

The mine Alcaparrosa lies on the west side of Cerro Alcaparrosa, about 3 kilometers southwest of the station of Cerritos Bayos on the railroad from Antofagasta to La Paz, Bolivia. This deposit should not be confused with the more famous sulphate deposit of the same name at Tierra Amarilla, near Copiapó, Chile. The property is reached by an auto road from Cerritos Bayos. It is near the base of the hill, a peak that dominates the landscape in this vicinity. The deposits consist of a series of veins and lenses of varying strikes and dips.

History. There are a number of small, massive isolated sulphate deposits at this property that have been mined over a long period. The deposit is remarkable in the total absence of copper, a feature that distinguishes it from any similar pyritic deposit in northern Chile known

to the writer. Due to the total absence of any other metal, the deposit has had a very limited value. The first work is reported to have been carried on in about 1875. Minerals from the deposit began to be described in Germany about 1880.

The sulphates were first mined for their sulphuric acid content. Inclined pits were sunk on the veins and roemerite and coquimbite were sought as the more favorable minerals. When dissolved in water, roemerite yields free acid, while solutions of coquimbite, when heated, yield free acid through precipitation of iron oxide. These acid solutions were used in leaching copper and silver ores. The large amount of iron in the solutions which would precipitate with the greatest of ease was a great drawback to their use. Mining ceased in the late nineties and was resumed about 1917 but ceased again about 1920. The area may have produced 20,000 tons of sulphates. There may be 5,000 tons of sulphates still available in the present workings and an unknown amount in undeveloped veins. However, of the material in sight, much is in the form of basic sulphates which have little or no value as a source of acid.

This deposit is the type locality for amarantite and hohmannite, for crystals of metavoltine, and for the orthorhombic form of butlerite, parabutlerite. It has yielded an undetermined mineral related to the alums, described in this paper.

Geologic History. The sulphates occur in flows near the base of Cerro Alcaparrosa. The writer believes the deposits to be no older than the Pliocene. They represent oxidized portions of pyritic masses formed close to the surface that have later been subjected to oxidation under increasingly arid conditions. Since Pliocene times erosion has not been great and there has been slight downward migration of the iron and sulphur.

The geochemistry of the deposit is discussed in detail under the section on Paragenesis.

PARAGENESIS

The paragenesis of the oxide minerals in these three deposits will be discussed under two headings—Sequence of Deposition and Geochemistry.

Sequence of Deposition. The sequence of deposition of minerals formed in the oxide zone of ore deposits has been hard to establish. The opaque minerals have been studied intensively, but the far greater number of nonopaque minerals have received little attention. Statements of depositional sequence of these oxide minerals are rare in the literature of ore deposits. Such sequences are established with difficulty. Physical conditions, as well as the chemical composition of the meteoric solutions

passing downward through a deposit, change rapidly from time to time and from place to place. The change in the composition of the solutions may be periodic and give rise to repeated deposition of a certain sequence with complete or partial solution or replacement of the older minerals. There are many factors that may cause oxide minerals to be deposited: among them are degree of saturation, change in alkalinity, loss of volatile gases, change in temperature, change in pH . Meteoric waters passing downward dissolve the more soluble minerals or salts first and the less soluble salts later, and unless reactions take place in the solutions these minerals will be redeposited at lower levels. Minerals formed at one time may, at a later time, be wholly or partially redissolved and the fortuitous presence or absence of some other mineral may completely change the character of the next generation of minerals. Oxygen plays an important role, and the availability of this element in the more open channels as contrasted with the solid country rock may give rise to two different groups of minerals deposited from otherwise identical solutions.

In most mining districts, water, one of the essential agents of oxidation, is supplied at more or less regular intervals in sufficient quantity to prevent the water throughout the deposit from becoming uniform in composition for any appreciable period of time. With a more or less constant supply of water, these meteoric solutions rarely build up a uniform concentration of either acids or bases over any appreciable area of the deposit. There is always an abundance of the solvent, and the soluble minerals are rapidly transported to the ground water reservoir. Only the relatively insoluble oxide minerals are left in the supergene zone. As a result, most ore deposits have a relatively limited number of minerals in the supergene zone, minerals that will form from very dilute solutions and once formed are relatively stable, for example, hydrous iron oxide.

In northern Chile, conditions are exceptionally favorable for the formation of sulphates, chlorides and oxides from concentrated solutions and from solutions that maintain a uniform composition over long periods of time. In the three deposits considered in this study, the water table is far below the surface and the primary sulphide horizon, with the exception of portions of Chuquicamata. Rains capable of adding an appreciable amount of water to the deposit, that is, a sufficient amount to even moisten the entire oxide zone, only occur once in a decade as a rule. During the intervening periods the sulphates form from concentrated solutions and then, once formed, change very slowly. There can be no question but that many of the sulphates form from older sulphates through reactions taking place in moist air and not by precipitation from aqueous solutions.

As a case in point showing the difference between the character of deposition of sulphate minerals from concentrated solutions, with essential stability between the solid and liquid phases, and sulphates deposited from supersaturated solutions where no stability exists between the two phases, the famous sulphate deposit of Mina Alcaparrosa at Tierra Amarilla, Chile, might be mentioned. This deposit on the banks of the Rio Copiapó receives periodic rains but in scant quantity, as a rule insufficient to penetrate far into the older sulphates. The original sulphide was pyrite in large echelon lenses. Under more moist conditions than those existing today, the pyrite was oxidized to a number of iron sulphates. The sulphates were present to within a few feet of the surface



FIG. 3. Sketch of a specimen of zoned sulphates from Quetena, showing distribution of the minerals present.

- | | |
|----------------------------|-------------------------------|
| 1. Pyrite and szomolnokite | 6. Alums |
| 2. Pyrite and halotrichite | 7. Pisanite, var. salvadorite |
| 3. Copiapite | 8. Botryogen, var. quetenite |
| 4. Jarosite | 9. Copiapite and botryogen |
| 5. Parabutlerite | 10. Altered country rock |

and when the deposit was mined a few pillars of the original sulphates were left which are exposed on four sides and have dried out almost completely. As a result, when rain falls on these pillars the water rapidly becomes saturated and supersaturated and then redeposits the sulphates. The solutions penetrate only a few inches into the pillars and their effect is relatively limited. During the dry periods that follow the rains, the pillars dry rapidly and there is little bulk effect from the rain such as would exist if the deposit was a large unit, exposed only on the surface. The effect of the deposition from supersaturated solutions is to form a crust of fine-grained sulphates on the pillars, sulphates composed of normal and basic varieties deposited simultaneously. Underneath this surface crust is a more or less solid mass of basic sulphates that show essentially definite sequence of deposition or formation. These original sulphates were formed under conditions of relative stability, and this permitted the formation of large masses of single mineral species.

Since the sulphates of the deposits here described are derived from pyrite, the general sequence as here given begins with that mineral. In a zoned alteration of a pyrite nodule (Fig. 3), the outer portion is altered first, and, as the alteration proceeds inwards, the sulphate already produced undergoes successive changes in composition, again from the outer rim inward. The sequence from pyrite is given, therefore, by the minerals from the pyrite core outward with the outermost mineral the last to form. This last mineral is in the terminology of this paper the "late" mineral, where pyrite is the "early." This treatment has led to certain relationships that appear to be ambiguous. Pickeringite and halotrichite, as well as fibroferrite, appear as recent efflorescent minerals on the walls of openings in these deposits, forming after all other minerals. Yet both are early minerals, especially halotrichite, which is a normal hydrous ferrous aluminum sulphate. The early crystals of halotrichite often contain inclusions of unoxidized pieces of pyrite. The recent formation of these minerals is probably due to their solubility and a wide depositional range from solutions that are not in stable relationships.

Under average conditions the sulphates and chlorides form in the following order, as determined in this study.

SEQUENCE OF SUPERGENE HYDROUS SULPHATES AND CHLORIDES

<i>Late</i>	Hydrous oxides (limonite)	
	Hydrous basic salts	small percentage of H_2O
	Hydrous basic salts	large percentage of H_2O
	Hydrous normal salts	large percentage of H_2O
	Hydrous normal salts	small percentage of H_2O

	Hydrous acid salts	large percentage of H ₂ O
Early	Hydrous acid salts	small percentage of H ₂ O

The above generalized sequence is based, primarily, on a study of the pure hydrous iron sulphates. Departures from this sequence are common, but the "key" minerals in all deposits studied follow this sequence as a rule. "Key" minerals are those minerals that appear frequently in all parts of a given deposit and in different deposits and to which associated minerals can be referred on the basis of sequence of formation. The presence of sodium, calcium, potassium, and magnesium in the sulphates has an effect on the generalized sequence, but this could not be evaluated in this study and no definite conclusions were reached. Additional studies need to be made upon either single veins in similar deposits or upon deposits with a relatively simple and limited mineral assemblage. As seen in the following table, normal hydrous sulphates carrying one of these elements may form with basic iron and copper sulphates. It is realized, of course, that the sequence relationships of these minerals as here determined may be in error and that all sulphates do not follow the sequence outlined above.

Table I represents an attempt to bring together a number of individual sequence determinations. Single specimens or suites of specimens give definite relationships. Key minerals in different groups were correlated and the intermediate minerals were fitted together as closely as the data permitted. The following tabulation of some sequence relationships at Quetena illustrates the difficulties and limitations of the method used.

ACTUAL SEQUENCES		CORRELATED SEQUENCES	
Copiapite	Copiapite	Copiapite	Copiapite
	Coquimbite	Voltaite	Voltaite
		Coquimbite	Coquimbite
		Quenstedtite	Quenstedtite
	Roemerite		Roemerite
Halotrichite			Halotrichite
	Szomolnokite	Szomolnokite	Szomolnokite
Chalcocite			Chalcocite
Pyrite		Pyrite	Pyrite

In Table I more than one sequence is given for Chuquicamata and Quetena. In these deposits it was difficult to determine the relationships between the different occurrences, and it was thought better to give separate lists rather than to try to combine them all into one list on too little data regarding interrelationships. The paragenetic associations of

these minerals will be discussed in the following section on geochemistry, and more fully under the individual species.

TABLE I. MINERAL SEQUENCE AT CHUQUICAMATA, QUETENA, AND ALCAPARROSA, CHILE
A. CHUQUICAMATA

1	2	3
SUPERGENE SULPHIDES	SUPERGENE OXYGEN-BEARING MINERALS	
Chalcocite	Northeast Section—	Central and Western
Covellite	Area of Heavy Pyrite	Sections
Bornite	Veins	
Chalcopyrite		
	<i>Late</i> Limonite	Limonite
PRIMARY MINERALS	Kalinite	Gypsum
	Natrojarosite	Cuprite
<i>Late</i> Covellite	Natroalunite	Molybdic ocher
Enargite	Antlerite	Sulphur
	Cuprocopiapite	Natrojarosite
Fracturing	Picromerite	Picromerite
	Parabutlerite	Antlerite
Bornite	Amarantite	Lindgrenite
Chalcopyrite	Hohmannite	Natroalunite
Pyrite	Copiapite	Natrochalcite
	Fibroferrite	Atacamite
Fracturing	(Tamarugite)	Leightonite
	Aluminite	Turquois
Pyrite	Metasideronatrite	Bloedite
	Metavoltine	Kroehnkite
Fracturing	Ferrinatrite	Chalcanthite
Magnetite	Tamarugite	
<i>Early</i> Hematite	Coquimbite	
	Roemerite	
	<i>Early</i> Halotrichite	
4	5	6
SUPERGENE OXYGEN-BEARING MINERALS (Cont.)	PARAGENESIS NOT ESTABLISHED	
Southeast Area	East Side, Weakly Sulphatic	Sphalerite
		Tetrahedrite
Opal	Brochantite	Soda Niter
Chrysocolla	Tenorite-manganite-limonite	Mirabilite
Azurite	Cuprite	Thenardite
Malachite	Native Copper	Cerussite
Atacamite		Chenevixite
		Pisanite
		Calcite
		Magnesite
		Halite
		Ulexite

in the field and in the laboratory, although the laboratory experiments have not been as successful in furnishing data as was hoped for.

More progress has been made and more definite conclusions reached in the study of the various oxide systems, in particular $\text{CuO-SO}_3\text{-H}_2\text{O}$ and $\text{Fe}_2\text{O}_3\text{-SO}_3\text{-H}_2\text{O}$. The former system was studied most successfully by Posnjak and Tunell.² The latter system was studied by Posnjak and Merwin and others.³ These works are not in entire agreement and the work of Posnjak and Merwin is here taken as the best available.

The geochemistry of the oxidation at Alcaparrosa where no copper is involved and at Chuquicamata where copper is an important constituent will be discussed in detail, while the oxidation at Quetena will be considered in relation to these two deposits.

Oxidation at Alcaparrosa, Chile

There are two types of oxidation at Alcaparrosa, or what might be called "two lines of descent," one involving iron sulphates, or sulphates carrying iron, the other involving non-ferrous sulphates, principally alums. For comparison with the work on the system $\text{Fe}_2\text{O}_3\text{-SO}_3\text{-H}_2\text{O}$ the two lines will be discussed separately.

In one of the inclined pits at Alcaparrosa a complete series of sulphates from the surface to fresh pyrite was exposed. This series is described here in detail to give a picture of the deposit. The different pits on the property show different minerals, but the relationships are, in general, the same. The section from the surface to the bottom is as follows:

1. Alluvium, 1-4 feet.
2. Mirabilite altered to thenardite with associated nitrates, 8 inches. Spotty and variable in thickness. Probably not genetically related to the pyrite deposits.
3. A white pulverulent mixture of several minerals, mostly alums with some gypsum, variable in thickness, usually in pockets.
4. A hard to pulverulent brown manto of jarosite and iron oxide, 1 to over 6 inches thick.
5. In isolated areas, brown to orange parabutlerite. Evidently an alteration product of the underlying copiapite. At the bottom this layer becomes distinctly fibrous in character with the general appearance of fibroferrite. Average, 8 inches thick.
6. A layer of variable thickness of greenish-yellow to brown copiapite. The crystals are minute in size as a rule. Large, megascopic, brilliant yellow crystals are developed only

² Posnjak and Tunell, *Am. Jour. Sc.*, vol. 18, p. 1, 1929.

³ Posnjak and Merwin, *Jour. Am. Chem. Soc.*, vol. 44, p. 1965, 1922; Merwin and Posnjak, *Am. Mineral.*, vol. 22, pp. 567, 1937.

Cameron and Robinson, *Jour. Phys. Chem.*, vol. 11, p. 641, 1907.

Wirth and Bakke, *Zeits. anorg. Chem.*, vol. 87, p. 13, 1914.

Scharizer, *Zeits. Krist.*, vol. 43, p. 125, 1907; vol. 46, p. 432, 1909; vol. 52, p. 385, 1913, etc.

Baskerville and Cameron, *Jour. Phys. Chem.*, vol. 39, p. 769, 1935.

where country rock occurs. A feature of this layer is the occurrence in the copiapite of coarse, bladed, pale bluish-white, milky pseudomorphs of coquimbite after quenstedtite. The copiapite is the younger mineral and the crystals show little evidence of replacement by the copiapite. Thickness, 0-12 inches.

7. A massive layer of light purple, finely crystalline coquimbite. The upper contact with the copiapite is sharp, as a rule. The layer grades downward into the lower bed. Thickness, 2-10 inches.

8. A massive layer of dark purple and reddish purple coquimbite and roemerite, intimately associated. The roemerite is replaced by the coquimbite. Crystals and crystal druses are abundant. Associated with the coquimbite, in vugs, are crystals of lapparentite, pickeringite, quenstedtite and pseudomorphs of coquimbite after quenstedtite. Large crystals of coquimbite, up to $\frac{3}{4}$ inch, occur in the more massive replaced quenstedtite. At the bottom of the horizon rounded masses of bright yellow roemerite appear. Thickness, 3-20 inches.

9. A layer of variable composition. At the top is massive coquimbite with round, isolated areas of szomolnokite and pyrite, surrounded by a layer of roemerite. The coquimbite grades downward into massive reddish-brown roemerite with rounded areas of yellow roemerite. The same round areas of szomolnokite and pyrite occur in the roemerite as well as in the coquimbite. These areas may vary from a fraction of an inch to several inches in diameter. Thickness from 3 inches to 2 feet.

10. A layer of unknown thickness but certainly up to two and a half feet thick of colorless and faintly brownish-purple rhomboclase and intimately associated szomolnokite with bright angular pieces of pyrite scattered through the minerals. Where the pyrite is most abundant the szomolnokite increases in abundance in relation to rhomboclase. The contact between the upper bed of roemerite and the rhomboclase-szomolnokite is line-sharp and apparently plane. There is no apparent change in texture as one passes from the colorless rhomboclase to the reddish-brown roemerite.

From this section the following sequence can be more or less definitely established.

SEQUENCE I		SEQUENCE II	
Mirabilite—soda niter			
Alums—gypsum			
Jarosite	$\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6$	Basic	
Parabutlerite	$\text{Fe}_2(\text{SO}_4)_2(\text{OH})_2 \cdot 4\text{H}_2\text{O}$	Basic	
Copiapite	$\text{Fe}_4(\text{SO}_4)_6(\text{OH})_2 \cdot 16\text{H}_2\text{O}$	Basic	
Quenstedtite	$\text{Fe}_2(\text{SO}_4)_3 \cdot 10\text{H}_2\text{O}$	Normal	
Lapparentite	$\text{Al}_2(\text{SO}_4)_2(\text{OH})_2 \cdot 9\text{H}_2\text{O}$	Basic	
Pickeringite	$\text{MgAl}_2(\text{SO}_4)_4 \cdot 24\text{H}_2\text{O}$	Normal	
Coquimbite	$\text{Fe}_2(\text{SO}_4)_3 \cdot 9\text{H}_2\text{O}$	Normal	
Quenstedtite	$\text{Fe}_2(\text{SO}_4)_3 \cdot 10\text{H}_2\text{O}$	Normal	
Roemerite	$\text{Fe}'' \cdot \text{Fe}_2'''(\text{SO}_4)_4 \cdot 14\text{H}_2\text{O}$	Normal	Roemerite
			Rhomboclase $\text{Fe}_2(\text{SO}_4)_3$
			$\cdot \text{H}_2\text{SO}_4 \cdot 8\text{H}_2\text{O}$ Acid
Szomolnokite	$\text{FeSO}_4 \cdot \text{H}_2\text{O}$	Normal	Szomolnokite
Pyrite	FeS_2		Pyrite

It is at once apparent that in the sequence outlined above the otherwise orderly change from acid or normal sulphates to later basic sul-

phates and from ferrous to ferro-ferric to ferric sulphates is interrupted by rhomboclase. If the field occurrence is taken at its face value, we have (Sequence II) a normal ferrous sulphate, szomolnokite, altering to an acid ferric sulphate, rhomboclase, and this in turn altering to a normal ferro-ferric sulphate, roemerite. In the other case (Sequence I) we have a normal ferrous sulphate altering to a normal ferro-ferric sulphate, and this in turn to normal and then basic ferric sulphates. It is believed that some localized circumstance, explained in a later section, caused the formation of rhomboclase in the place it now occupies in the deposit.

No study has been made of either of the systems $\text{FeO-SO}_3\text{-H}_2\text{O}$ or $\text{FeO-Fe}_2\text{O}_3\text{-SO}_3\text{-H}_2\text{O}$, but Posnjak and Merwin⁴ have studied the system $\text{Fe}_2\text{O}_3\text{-SO}_3\text{-H}_2\text{O}$ from 50 degrees to 200 degrees. They obtained rhomboclase, copiapite and monoclinic butlerite among the artificial minerals formed at the lower temperatures. The minerals obtained and the solutions from which they formed at 50 degrees are tabulated below.

MINERAL	LIQUID PHASE			
	Weight Per Cent			
	Fe_2O_3	SO_3	H_2O	$\text{SO}_3/\text{Fe}_2\text{O}_3$
Rhomboclase	0.09- 5.55	55.34-33.96	44.57-60.49	6.15-6.1
Copiapite	16.78-21.00	30.72-28.2	52.50-50.8	1.8 -1.3
Butlerite	21.00-20.13	28.2 -27.18	50.8 -52.69	1.3

Also within the range studied, the various classes of iron sulphates were obtained from liquids of the composition noted below.

CLASS	LIQUID PHASE			
	Weight Per Cent			
	Fe_2O_3	SO_3	H_2O	$\text{SO}_3/\text{Fe}_2\text{O}_3$
Acid	0.00- 5.55	75.37-33.96	24.56-60.49	Inf. -6.1
Normal	8.56-16.78	32.52-30.72	58.92-52.50	3.8 -1.8
Basic	16.78- 0.14	30.72- 0.39	52.50-99 47	1.8 -2.8

It is observed from these data that sulphuric acid content is the dominating factor in the type of sulphate formed. It is also noteworthy that many of the sulphates so abundant in nature were not obtained in these studies, coquimbite for example.

Scharizer and others have obtained a number of artificial salts that correspond to natural minerals in various experiments. Some of these data, in compositional ratios, are given here for comparison with natural

⁴ *Op. cit.*

sequence relations of the minerals and for comparison with the data of Posnjak and Merwin given above.

	weight per cent
Szomolnokite	$\text{H}_2\text{O}/\text{SO}_3 = 2.186-7.93^5$
Copiapite and coquimbite	$\text{Fe}_2\text{O}_3:\text{SO}_3:\text{H}_2\text{O} = 1:3.47:30.88^6$
Coquimbite and rhomboclase	$\text{Fe}_2\text{O}_3:\text{SO}_3:\text{H}_2\text{O} = 1:6.69:55.77^6$
Copiapite	$\text{Fe}_2\text{O}_3:\text{SO}_3:\text{H}_2\text{C} = 1:6.45:41.94^7$
Rhomboclase	$\text{H}_2\text{O}/\text{SO}_3 = 3.744-3.664^7$

There are some additional data, mostly by Scharizer, but there is serious doubt as to whether his solutions reached equilibrium. The data are, therefore, of little value in this connection and are not quoted here, although his findings check the sequences determined in these deposits. This might be expected, as many of these natural sulphates formed from solutions that had not reached a state of equilibrium with the solid phases.

From the foregoing data it is apparent that acid, normal and basic salts are deposited in this order from solutions that are more and more dilute and from solutions in which the acid content decreases in proportion to the iron, although in the very dilute solutions the actual ratio increases a little.

The writer offers the following explanation for the formation of rhomboclase at Alcaparrosa. It is believed to be later than the roemerite and szomolnokite with which it is associated, and to be a sulphate derived from the oxidation of these two minerals. The szomolnokite formed first from the oxidation of the pyrite under conditions of limited water and oxygen. It was then partially oxidized under similar conditions to roemerite. At some subsequent period, while this process of oxidation was still going on, probably after it was well advanced, sufficient moisture appeared in the deposit to allow the formation of a water table, and this probably maintained a given horizon for some time in the bottom of the deposit. The water contained a high percentage of salts and was relatively strongly acid. In this water, sufficient oxygen was present, and was added from time to time, to oxidize the roemerite and part of the szomolnokite to the acid sulphate rhomboclase. An origin of this nature would explain the more or less horizontal, exceptionally sharp contact between the roemerite and rhomboclase-szomolnokite mixture. It would also explain the complete oxidation of the roemerite, a readily soluble sulphate, and the partial oxidation of the ferrous sul-

⁵ Kenrick, *Jour. Phys. Chem.*, vol. **12**, p. 699, 1908.

⁶ Wirth and Bakke, *Zeits. anorg. Chem.*, vol. **87**, p. 40, 1914.

⁷ Scharizer, Doelter, 4 pt. 2, 572, 1929.

phate szomolnokite, which is less soluble and would require more oxygen and acid to oxidize it to an acid ferric sulphate.

The relationships of coquimbite and quenstedtite are noteworthy. These minerals have the composition:

Quenstedtite	$\text{Fe}_2(\text{SO}_4)_3 \cdot 10\text{H}_2\text{O}$
Coquimbite	$\text{Fe}_2(\text{SO}_4)_3 \cdot 9\text{H}_2\text{O}$

According to the general sequence relationships of the sulphates, coquimbite would be expected to form first and then be followed by quenstedtite. The relationship is, in general, in agreement with this sequence, but there is a marked overlap of the period of the two minerals. As a result there appear to be two ages of quenstedtite, one replaced by coquimbite and one later. The dull, pale blue, milky pseudomorphs probably formed as quenstedtite at the same time as coquimbite was forming. The coquimbite had the power to replace the quenstedtite under certain conditions, while the reverse replacement was apparently difficult or impossible. The coquimbite would form from the more acid and more concentrated solutions, and after a rain or some influx of water into the deposit the first solutions would be diluted and quenstedtite would form and as the solutions became more acid and more concentrated the depositional range for coquimbite would be reached and it would form and at the same time replace the older quenstedtite. This type of deposition went on during the latter half of the coquimbite period. The small amount of crystallized quenstedtite may have formed along with lapparentite and pickeringite. The formation of these minerals will be discussed later but the conclusions reached will be applicable, probably, to the formation of crystals of quenstedtite that have not been replaced by coquimbite. Theoretically, a point is reached in the deposition of sulphates from a solution where the solid phase is not readily soluble and minerals are deposited from solutions that are less and less concentrated. If this is true, quenstedtite would have a period of formation later than coquimbite and the crystals of this mineral may have formed in this manner, from more dilute solutions.

All of the basic iron sulphates are later than the normal sulphates. The relationship of copiapite and later parabutlerite is definite in both the hand specimen and in the field. The natural occurrence coincides exactly with the data obtained on artificial systems. At the contact of parabutlerite and copiapite much of the parabutlerite retains the platy, radiating structure of the copiapite, from which it is derived.

The conditions of formation of the non-ferrous sulphates cannot be treated with the same assurance as the pure iron sulphates. In the field their volume is much less in these deposits and their occurrence is spotty.

Minerals that are compound sulphates of iron and some other element are more abundant, but they shed little light on the sequence of the non-ferrous sulphates. Potassium and sodium may appear in these minerals along with the iron but there is no consistent relationship.

Jarosite is definitely a late mineral. This is a potash-iron sulphate and at Alcaparrosa occurs above the parabutlerite. Other near-surface compound sulphates carrying iron are:

Botryogen	$\text{Mg}_3\text{Fe}_2(\text{SO}_4)_4(\text{OH})_2 \cdot 14\text{H}_2\text{O}$
Metavoltine	$(\text{K}, \text{Na})_2\text{Fe}_2(\text{SO}_4)_4 \cdot 8\text{H}_2\text{O}$

Botryogen is abundant in one of the pits as a late mineral, later than copiapite with which it is associated. The only other associated minerals are kalinite and mendozite, potassium and sodium alums. Metavoltine occurs in rather definite, narrow relationships. It occurs near the surface associated with copiapite and various alums, both of which are younger minerals.

From these associations it is evident that the alums, normal sulphates, are late minerals. Associated with the lapparentite, a basic sulphate, are pickeringite and iron sulphates.

<i>Late</i>	Copiapite	$\text{Fe}_4(\text{SO}_4)_6(\text{OH})_2 \cdot 16\text{H}_2\text{O}$
	Pickeringite	$\text{MgAl}_2(\text{SO}_4)_4 \cdot 24\text{H}_2\text{O}$
	Lapparentite	$\text{Al}_2(\text{SO}_4)_2(\text{OH})_2 \cdot 9\text{H}_2\text{O}$
	Quenstedtite	$\text{Fe}_2(\text{SO}_4)_3 \cdot 10\text{H}_2\text{O}$
<i>Early</i>	Coquimbite	$\text{Fe}_2(\text{SO}_4)_3 \cdot 9\text{H}_2\text{O}$

It is difficult to explain the formation of a basic aluminum sulphate preceded and followed by normal sulphates. However, the lapparentite is present in a very limited quantity. In other areas of the deposit, near the surface, lapparentite is a later mineral and follows and is followed by alums. However, the writer is rigorously following the sequence determinations on individual specimens; and, while in the deposit, in general, there is as much evidence that lapparentite is a late mineral as an early one, in this case it is definitely followed by pickeringite, a mineral closely related in composition to the alums.

As stated above, the alums are late minerals, all of them being normal sulphates and forming later than basic iron sulphates. Much of the pickeringite is in the form of radiating acicular crystals growing on other crystals in vugs and veins. The last mineral to form in present openings, covering the walls of many of the pits as an efflorescence is the basic ferric sulphate fibroferrite, $\text{Fe}_2(\text{SO}_4)_2(\text{OH})_2 \cdot 9\text{H}_2\text{O}$. This mineral offers the key to certain anomalous minerals, especially those present in minor quantities, which form under conditions of limited hydration. With no

water present in liquid form it is possible for them to form throughout the deposit. As in the case of lapparantite and pickeringite, on coquimbite, in the bottom of the deposit, the minerals may have altered from earlier formed minerals but a short time previous to removal and are now in association with early minerals and in zones beneath minerals that are much older. At Chuquicamata we find fibroferriite associated with amarantite, hohmannite and botryogen where it has formed earlier than any of these minerals from acid, aqueous solutions. Likewise we find it as an efflorescence of very recent origin in vugs, etc., the product of hydration.

The conclusion reached is that minerals of this type can form in any opening when sufficient water vapor is present. These hair-like forms grow out from the walls or from the support by addition of material to the bottom of the crystal, that is, the point of support of the crystal. The writer has observed the formation of fibroferriite at Quetena in this manner after a moist period, and specimens of metavoltine, copiapite and rhomboclase began to develop fibroferriite on their surfaces after exposure in laboratories in the United States for a few months.

The problem of the sequence of the non-ferrous sulphates must be left open. Where the minerals contain both iron and some other base, isolated sequence relationships can be determined at Alcaparrosa, but with the pure non-ferrous sulphates a consecutive sequence cannot be determined in relation to the iron sulphates. Most of them are later than the iron minerals. Since the non-metallic elements are obtained from the country rock, reactions between the sulphate solutions and the wall rock would probably tend to dilute the solutions, and variations in the intensity of reactions and degrees of dilution might account for the variations in the sequence of formation found in this study.

Oxidation and Enrichment at Chuquicamata, Chile

At Chuquicamata and to a less degree at the two smaller sulphate deposits, the oxidation of the ore has resulted in a rather wide distribution of the valuable metals and, as a rule, no sharp horizons of demarcation between leached capping, enriched zone and primary sulphides exist. The rapidity of oxidation of the pyrite-enargite veins was roughly proportional to the ratio of pyrite to enargite. In the massive enargite veins to the northeast, oxidation was slow, and many veins show enargite near the surface, while in the area of disseminated enargite and in areas of abundant pyrite the zone of oxidation is much deeper and oxidation must have been much more rapid. While similar minerals have formed in almost all areas, especially the common and abundant minerals, some of the rarer minerals are limited to definite areas at Chuquicamata, and

these rarer minerals offer much information regarding the conditions of formation of associated minerals.

In all cases, the first product of enrichment was chalcocite. This mineral occurs throughout the deposit but is most widely distributed through the porous sericitic rock along the western edge. In the central area of the deposit, rare occurrences of supergene(?) chalcopyrite older than chalcocite occur in massive chalcocite. This chalcopyrite is in the form of rounded, scattered grains.

Much of the chalcocite, probably most of it, formed through reactions of copper sulphate and pyrite and is found today very intimately associated with this sulphide. It has been estimated⁸ that it would be necessary to crush the Chuquicamata ore to four microns in order to release enough chalcocite to make a 90% recovery by flotation, and obtain a 65% copper concentrate.

Along the east side of the deposit, in the area to the northwest and in the vein zone northeast of the present pit, cuprite formed intimately associated with native copper. Associated with these minerals along the east side is tenorite and manganese oxides forming a "copper pitch ore." No satisfactory reaction can be given for the formation of this minor occurrence. Whatever the cause, the one feature evident in the field is that these oxide minerals and the native copper formed in an environment that was less acid than that of the great bulk of the supergene minerals. Most writers believe that native copper and cuprite form from essentially neutral or alkaline solutions. In the northwest the cuprite formed from veins carrying primary carbonates.

Another occurrence of native copper and minor cuprite intimately associated with specularite has been discovered by drilling along the eastern edge of the deposit. The shape and extent of this deposit were not delineated but the mass is essentially tabular, elongated parallel to the length of the main deposit. A feature of the occurrence is the intimate association of specularite and native copper with minor cuprite in cubic crystals. Some iron oxide is present but is not abundant. More detailed knowledge of the occurrence is necessary before the origin can be established. It may represent the formation of cuprite and copper after chalcocite through the action of ferric sulphate in a neutral environment or the specularite may be involved in the origin.

Cuprite forms after and from native copper at Chuquicamata. Characteristically the copper occurs as small to minute grains scattered through the cuprite, or, as mentioned above, the cuprite occurs as crystals on native copper. The massive cuprite occurs as kernels or veins surrounded by "copper pitch" and this, in turn, by chrysocolla and opal. Along the

⁸ Bandy, Private report, 1931. See Taylor, *op. cit.*

extreme eastern side of the deposit the "copper pitch" occurs in pure masses, round to tabular in shape. Some of the round masses are three feet in diameter. The ore is black with pitch-like luster in the center and grades to a soft dark brown mass on the border. This material is discussed under the name "Copper Pitch." Cuprite is also present as a late supergene mineral, pseudomorphic after antlerite. This will be discussed later.

In the bulk of the deposit at Chuquicamata the hypogene sulphides were deposited as small veins and disseminations through the "quartz-sericite," "normal rock" and to a minor degree in the "transition rock" types. These sulphides have weathered deeply except in areas of intense quartz flooding. In this part of the deposit the sequence relationships are clearer, and some of the oxidation reactions are more obvious than around the outer fringe.

The difficulty of oxidizing enargite is well known. The reason for the deep alteration at Chuquicamata is believed to be due to the disseminated character of the enargite as mentioned above, and to the abundance of associated pyrite. The latter mineral furnished the necessary iron (ferric?) sulphate, which could attack the small and isolated grains and small veins of enargite more effectively than large massive veins. It would appear that ferric sulphate rather than ferrous sulphate is involved in the oxidation of enargite with the formation of arsenate minerals. While arsenate minerals are not unknown at Chuquicamata, on the whole they may be considered as rather rare. There are a few isolated areas where chenevixite occurs. The weathering of the great mass of enargite at Chuquicamata has released a large quantity of arsenic, and whether this arsenic was carried away during the Tertiary period in solution or was fixed in the outcrops during this period as some arsenate mineral and then removed by the post-Pliocene erosion cannot be determined.

With the oxidation of the enargite, pyrite and minor covellite, the copper was carried downward and deposited from acid sulphate solutions on other pyrite and enargite as chalcocite. The replacement proceeded inwardly, and bladed enargite structures are preserved in some of the supergene chalcocite. This supergene chalcocite was later altered to oxide minerals. As a rule, the first mineral to form from the chalcocite and pyrite is chalcantite, and in near-surface areas chalcantite and kroehnkite, $\text{CuNa}_2(\text{SO}_4)_2 \cdot 2\text{H}_2\text{O}$. Field evidence indicates that kroehnkite formed from less acid solutions than chalcantite. With an adequate supply of water these minerals would go into solution and pass downward as copper sulphate in ferric sulphate solutions. Upon encountering

chalcocite, free from pyrite or with only minor amounts, covellite might form first from the chalcocite and, in turn, alter to antlerite. Many sections of chalcocite show a band of coarsely bladed covellite between the antlerite and the chalcocite. The band of covellite advances into the chalcocite as the antlerite vein widens.

The excess of sulphuric acid developed during the formation of antlerite and the ready oxidation of ferrous sulphate probably is the reason for the general absence of cuprite and native copper at Chuquicamata, as both of these agents readily attack those minerals. Studies of artificial minerals have shown that antlerite forms from relatively concentrated solutions. Some of the free acid is removed by the attack on ever-present pyrite and less commonly on covellite, and on other minerals in the deposit. The attack on the pyrite would develop ferrous and ferric sulphates in place, due to the lack of solutions to carry them downward to a permanent water table. With little water, there is a constant recrystallization and little migration of newly formed salts. With the influx of additional water, sufficient to cause solution, such solutions would be concentrated after a very short migration, and minerals, antlerite in this case, would precipitate from the concentrated solution.

The formation of antlerite, $\text{Cu}_3(\text{SO}_4)(\text{OH})_4$, at Chuquicamata and other Chilean deposits, and of brochantite, $\text{Cu}_4(\text{SO}_4)(\text{OH})_6$, at almost every other basic copper sulphate deposit the world over (except at the Antler Mine in Arizona, the type locality) may be explained by the special conditions of acidity of the solutions at Chuquicamata. The characteristic feature of almost all the Chilean deposits is the presence of abundant soluble sulphates throughout the deposits with an excess of available acid. Specimens from these mines, when placed in water, will usually yield a solution containing free acid. By analogy, water entering these deposits would soon contain free sulphuric acid which would attack less soluble salts and in this manner rapidly increase the amount of material in solution. It is well known that the presence of limestone in a deposit tends to retard migration of sulphates through the removal of free acid from the solutions in the deposit and in fixing the sulphates as insoluble or difficultly soluble minerals. In contrast, at Chuquicamata little acid is removed in this manner; instead it forms soluble salts and much of the acid is readily available by resolution in water carrying oxygen.

In deposits elsewhere in the world, much of the sulphur is not fixed in the oxidized portion of the deposit but is carried downward to the water table. Thus any copper sulphates formed above the water table in these deposits would be deposited from dilute solutions as regards

content of both base and acid, except in rare or isolated cases. Tunell and Posnjak⁹ worked with a portion of the system $\text{Fe}_2\text{O}_3\text{-CuO-SO}_3\text{-H}_2\text{O}$ and their data support this theory. They found that brochantite formed from dilute solutions, solutions with a concentration less than,

CuO	SO ₃	H ₂ O
0.61	0.64	98.75

Antlerite formed from solutions with a concentration greater than,

CuO	SO ₃	H ₂ O
5.01	5.22	89.77

The antlerite is the end point in the copper enrichment at Chuquicamata. After forming, it is removed and carried downward in solutions containing iron sulphates with the precipitation of iron oxide either as a hydrate mineral or as hematite. The boxwork of the iron oxide after antlerite is believed to be characteristic of the mineral, and certainly the iron oxide itself is. It is known locally as "maroon oxide" and has a very distinctive deep red color and texture. Whatever the intermediate composition of the "maroon oxide" pseudomorphic after antlerite is, during the oxidation process, it changes eventually to a brown limonite which is stable.

Some of the ore at Chuquicamata shows the rare relationship of cuprite replacing antlerite. The pseudomorphs retain the fibrous structure of the antlerite in minutiae. The chemistry of this replacement is not clear. It probably results from the reduction of the antlerite by ferrous sulphate with a delicate balance in the proportion of ferrous sulphate to antlerite. These pseudomorphs occur only on the eastern side of the ore body in areas of low acidity.*

Four other minerals of uncommon or rare, but genetically significant occurrence at Chuquicamata are chrysocolla, brochantite, azurite and malachite. Chrysocolla is rare in the southeastern section of the deposit. It is confined to the "low acid" areas. The writer has found brochantite (identified optically) in this same area associated with gypsum. It also occurs in the northwest area associated with gypsum. As pointed out earlier, the study of artificial minerals showed that brochantite forms from more dilute solutions than antlerite, and one would expect to find more dilute solutions in these areas.

Malachite and azurite occur in an outlying vein to the south of the deposit. The gangue of the ore is coarse, bladed specularite and minor

⁹ Tunell and Posnjak, *J. phys. Chem.*, vol. 35, p. 929, 1931.

* By "low acidity" the writer refers to areas characterized by oxide minerals and few or no sulphates. At Chuquicamata low acidity areas are "more or less coincident with the Transition Rock type."

magnetite. Chrysocolla is an abundant mineral in this vein. The amount of malachite and later azurite is insignificant in proportion to other copper minerals, but significant in indicating the environment of deposition of these and associated minerals. The carbon dioxide in these minerals was probably derived from a small amount of carbonate gangue in the vein. It should be noted that gypsum is a near-surface mineral at Chuquicamata and is a most abundant mineral in the fringe of the deposit and in the alluvium about the mine. The bulk of the gypsum was not derived from the ore deposit, however.

Atacamite was an abundant mineral at Chuquicamata in the early years of the mine. This basic copper chloride, $\text{Cu}_4\text{Cl}_2(\text{OH})_6$, formed from the action of surface waters, charged with sodium chloride, on the soluble copper salts. The mineral is practically limited to the upper 70 feet of the deposit. It is more abundant in the "low acid" areas.

The massive iron sulphate veins in the northeast area of the mine should be mentioned briefly. The pyrite is oxidized first to halotrichite, $\text{FeAl}_2(\text{SO}_4)_4 \cdot 24\text{H}_2\text{O}$, and then in successive steps to fibroferrite, $\text{Fe}_2(\text{SO}_4)_2(\text{OH})_2 \cdot 9\text{H}_2\text{O}$, hohmannite, $\text{Fe}_2(\text{SO}_4)_2(\text{OH})_2 \cdot 7\text{H}_2\text{O}$, amarantite, $\text{Fe}_2(\text{SO}_4)_2(\text{OH})_2 \cdot 6\text{H}_2\text{O}$, botryogen, $\text{MgFe}(\text{SO}_4)_2(\text{OH}) \cdot 7\text{H}_2\text{O}$, and jarosite, $\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6$, with an introduction of Al_2O_3 , MgO , etc. The age relationships of botryogen are not clear. This mineral may be earlier than amarantite.

In other veins, probably veins that contained less primary pyrite or smaller veins, possibly areas of unusually strong dissemination of pyrite, metasideronatrite and metavoltine in intimate association, fibroferrite, ungemachite and clino-ungemachite and alums occur. These veins are not associated with the fibroferrite-amarantite veins and apparently the chemical or physical conditions of formation of the two associations were different. Almost all the minerals in these veins are soda-iron sulphates or soda-rich equivalents of potash-iron sulphates. The sequence is,

<i>Late</i>	Alums (soda)	$\text{Na}_2\text{Al}_2(\text{SO}_4)_4$	$24\text{H}_2\text{O}$
	Ungemachite	$\text{Na}_6\text{K}_2(\text{SO}_4)_4$	$8\text{H}_2\text{O}$
	Metasideronatrite	$\text{Na}_4\text{Fe}_2(\text{SO}_4)_4(\text{OH})_2$	$3\text{H}_2\text{O}$
	Ferrinatrite	$\text{Na}_4\text{Fe}_2(\text{SO}_4)_5$	$7\text{H}_2\text{O}$
<i>Early</i>	Metavoltine	$(\text{K}, \text{Na})_2\text{Fe}_2(\text{SO}_4)_4$	$7\text{H}_2\text{O}$

The alums are principally mendozite with a very small amount of kalinite, the potash alum.

This association represents an important feature of many deposits of northern Chile and especially of Chuquicamata. In this deposit, potassium sulphates are rare although the host rock is potash-rich. When the sulphates were formed, there was evidently an abundant source of

sodium that was taken up by the solutions moving down from the surface through the deposit. In every case, soda-rich minerals formed, such as natrojarosite, ungemachite, clino-ungemachite, or compound sodium sulphates such as those mentioned above. Corresponding potassium minerals did not form, while the sodium minerals mentioned above, as well as bloedite, mirabilite, kroehnkite and natrochalcite (the latter known only from this deposit) are common. This might well be called a "sodium province."

Two sources of the sodium can be postulated. One source is the sodium removed from the granodiorite during sericitization and orthoclasization. This sodium might have been carried upward to some horizon above the present deposit and there deposited as a sodium salt, possibly natroalunite, that would break down readily under weathering conditions. The one important point against this source is the presence of kroehnkite, metasideronatrinite and metavoltine in other Chilean deposits. The second source is the abundant soluble sodium minerals in the alluvium over almost all of northern Chile. These minerals include halite, soda niter, mirabilite, and thenardite, salts believed by the writer to be of volcanic origin. All of these minerals occur about the deposit at Chuquicamata today and have certainly been present since the volcanism of the Pliocene and probably since the early Tertiary. The writer has found lenses of nitrates, chlorides and borates in early Jurassic beds in this vicinity. Any circulating ground water would carry sodium in considerable quantity, and rain falling on the surface over the deposit would be charged with this element. On encountering iron and copper minerals or solutions of iron and copper sulphates, the sodium would form compound sulphates with these elements. The preponderance of sodium minerals in the oxide zones of ore deposits in northern Chile has never been sufficiently stressed. This second source of sodium seems the more likely.

Oxidation at Quetena, Chile

A study of the oxidation at Quetena adds little to the data obtained from Alcaparrosa and Chuquicamata. At the surface, near the contact with the limestone, float pieces of limestone are being replaced by brochantite and gypsum. These minerals occur in shells about the limestone. The association—carbonate, gypsum and brochantite—is similar to that at Chuquicamata. The basic hydrous copper chloride, atacamite, occurs at the surface and gives way in depth to bandylite and this mineral, in turn, to the normal chloride, antofagastite. The sequence of formation is,

<i>Late</i>	Atacamite	Basic
	Bandylite	Normal
<i>Early</i>	Antofagastite	Normal

If chlorides and sulphates follow the same general sequence in oxidation, can it be true that other classes of minerals follow it also? The carbonates do at Chuquicamata in the one specimen of malachite with later azurite examined by the writer. Both are basic carbonates, but malachite is the more hydrous. However, this relationship between malachite and azurite is not universal, as one mineral is later than the other in one deposit, and the reverse is true in other deposits. An outstanding example of malachite after azurite is found in the fine specimens from Tsumeb. It should be noted, however, that the Tsumeb ores are in a limestone and dolomite gangue and would not be entirely comparable to occurrences like Chuquicamata. At Tsumeb, as at many mines, azurite does form after some of the malachite. At Bisbee, malachite is both earlier and later than azurite, but the great bulk of the azurite is apparently later than the greater amount of the malachite. This same relationship is true at Chessy, France. At Clifton-Morenci, Lindgren¹⁰ states that azurite "is often the latest mineral formed." Lindgren also states that malachite follows brochantite at Clifton-Morenci, an identical relationship to that found at Chuquicamata. From these data the writer believes that the tendency for the carbonates to follow the general sequence of the sulphates is probable. Carbonates are most abundant, of course, in deposits in limestone. The sulphate sequence is established from deposits in a country rock that does not react to any appreciable extent with the oxidizing solutions.

No data are available for considering the other classes of minerals. The oxides, phosphates, arsenates, vanadates, etc., offer an interesting field of study in this connection.

An excellent example of the sequence relationships at Quetena is afforded by the specimen shown in Figure 3. The central core is composed of a mass of individual crystals of halotrichite, szomolnokite and pyrite. The minerals of the succeeding bands and the mineral sequence are tabulated below.

<i>Late</i>	Pickeringite	Normal
	Limonite	—
	Pisanite	Normal
	Botryogen	Basic
	Jarosite with alternating bands of copiapite	Basic
	Parabutlerite	Basic
	Copiapite	Basic
	Halotrichite	Normal
	Szomolnokite	Normal
<i>Early</i>	Pyrite	

¹⁰ Lindgren, *U. S. Geol. Survey, Prof. Paper 43*, p. 118, 1905.

It is to be noted that normal cupriferous minerals, such as pisanite, form after basic pure iron sulphates. This occurrence of copper minerals after iron minerals checks the work done by Tunell and Posnjak¹¹ on the system $\text{Fe}_2\text{O}_3\text{-CuO-SO}_3\text{-H}_2\text{O}$, since they show that when there is any appreciable concentration of iron in the solution, that is, Fe_2O_3 present in quantities greater than 0.01%, iron sulphates rather than copper sulphates form. A solution with the following composition:

Fe_2O_3	0.22%
CuO	0.94
SO_3	1.64
H_2O	97.20

formed a precipitate of $\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$ and $3\text{Fe}_2\text{O}_3 \cdot 4\text{SO}_3 \cdot 9\text{H}_2\text{O}$. It is evident that the copper is held in solution until the iron content falls to a trace, and then copper salts begin to form. In some parts of Quetena, cupro-copiapite formed by replacing copiapite, but only after copiapite, parabutlerite and jarosite had been formed. The same relationship is true at Chuquicamata.

PART II. DESCRIPTIVE MINERALOGY

The minerals are described under the same classification and in the same serial order as in Dana's "System of Mineralogy," sixth edition. Several new minerals are described and these are placed in serial order. The minerals, fully described, are treated in the following order:

- Crystallography
 - Forms
 - Structure Cell
 - Habit
 - Twinning
 - Cleavage
- Physical Properties
- Optical Properties
- Composition
- Pyrognostics
- Occurrence and Sequence
- References

Some species are described and discussed as a group as well. An attempt has been made to clear up some of the doubtful species that have come from the area described as well as species that are directly related to this study from other areas.

Minerals that are of slight importance to the study and minerals upon which no new data have been obtained are treated briefly. Minerals seen

¹¹ *Op. cit.*

only as essential constituents of the local country rocks are not included. Most of the new minerals described herein have been given names except where it was felt that they were not as yet adequately described.

An alphabetical list of the minerals described or discussed is given in the index.

NATIVE ELEMENTS

Sulphur

A few veinlets of sulphur were observed in the field in a small specimen at Chuquicamata. During the detailed study of the Chuquicamata suite, a number of magnificent, although minute, crystals of sulphur were found in one specimen. The specimen contained abundant dehydrated pisanite, chalcantite, rare crystals of kroehnkite, sulphur and cuboid natrojarosite in twinned crystals. The minerals are named in the order of their formation. The sulphur crystals were essentially spherical in shape and covered with faces. One crystal, less than a millimeter in diameter, was measured and found to have 120 faces. Two crystals showed 26 of the 34 known forms for sulphur. The known forms not observed were: (210) (120) (023) (337) (335) (553) (551) (344).

Ungemach¹* described similar crystals from the sulphate deposit at Alcaparrosa, Tierra Amarilla, Chile. These crystals were found on roemerite associated with lapparentite. Sixteen forms were observed.

The origin of the sulphur is an unsolved problem. Sulphur in ore deposits has been reported for a few mining camps of the Western United States, Monte Poni, Sardinia, and Mexico. Sulphur has also been reported from the Wheatley Mine, Pennsylvania. With the exception of Tierra Amarilla and Chuquicamata, all the ore deposits that have sulphur in the supergene zone are lead deposits. The origin of the sulphur in the Chilean deposits probably involves different processes than those that were active in the lead deposits. In Chile the sulphur was probably formed by the action of chlorides or hydrochloric acid on acid sulphates. Hydrochloric acid will precipitate sulphur from solutions of acid sodium sulphate.

REFERENCE. ¹ Ungemach, M. H., *Bull. Soc. Fran. Min.*, vol. 58, p. 97, 1935.

Copper

Native copper is rare at Chuquicamata as a natural mineral and is not known at Quetena. At Chuquicamata it occurs as residuals in cuprite and as small slugs or irregular masses in the southeast section of the deposit. The latter occurrence is in a somewhat tabular but ill-defined zone where the copper is associated with cuprite and much

* References are given at the end of each species.

specularite. The area was encountered during churn-drill prospecting and little is known regarding it. It is possible that the copper has resulted from the reaction between specularite and copper sulphate solutions with the result that iron sulphate formed and copper was precipitated. This assumes that the copper is supergene. As far as known, it occurs only in the transition rock, in an area where sulphates give way to silicates, oxides, and chlorides. Possibly some reaction involving chloride solutions may have given rise to the native copper.

In many of the old mines that have been worked to the water level, fluctuations of the water-table level have flooded the lower workings at different times. The waters are acid and charged with copper, and now all the available iron left in the mines has been replaced by spongy masses of native copper.

Gold

Gold is reputed to have occurred in quantity to the north of the present open pit at Chuquicamata. Repeated panning and assaying of the gravel and crushed quartz from this area has failed to reveal even a color. Nevertheless, old workings of the indigenes extend to depths of more than 75 feet. Their only interest could have been gold. There are a few spotty occurrences of gold along narrow fractures to the west of Chuquicamata but not in commercial quantities

SULPHIDES AND SULPHO-SALTS

Molybdenite

MoS₂ Hexagonal

Molybdenite occurs in plates and crystals at Chuquicamata in the northwest area, associated with primary chalcopyrite and bornite. It formed earlier than either of these sulphides.

As the open-pit mining extended to the west, the appearance of molybdenum in the ores and solutions at Chuquicamata caused a great deal of trouble in the mill. The molybdenum acted as a catalytic agent and prevented the precipitation of copper in the electrolytic plant. Thousands of mine samples were assayed for molybdenum, and the metal was found to be limited roughly to the western half of the deposit. The actual mode of its occurrence was not known, but it was believed to be present as "molybdic ocher." In 1932 the writer¹ recognized that the molybdenum was associated with narrow interlacing quartz veins on the western side of the deposit. These veins formed a rock type that had been mapped as "lacing veinlets." A number of assays of the vein material proved it to be comparatively high in molybdenum. The study

of about a hundred polished sections of these veins failed to give any positive proof of the exact state of the molybdenum in the veins, as all were oxidized and the amount of molybdenum present was usually less than 0.5%. Only occasional specks of a dark gray mineral gave any hint of the original mineral. The gray mineral had a hardness of four and gave etch tests that do not agree with any known mineral. The writer believes the mineral to be an iron-molybdenum sulphide.

REFERENCE. ¹ Private report, 1932. See Taylor, *op. cit.*

Chalcocite

Cu₂S Orthorhombic

Chalcocite is widespread at Chuquicamata and rare at Quetena. At the former mine it occurs as a supergene mineral to depths of over 2,000 feet, replacing pyrite and enargite. There is evidence of chalcocite zones formed at different elevations at Chuquicamata and, while some may have existed in pre-Tertiary times, the more distinct zones were formed in Tertiary times. Chalcocite occurs in all forms from disseminated grains to pure veins of massive sulphide up to eight inches wide. "Sooty" chalcocite is common on exposed surfaces in the abandoned mines, but most of this is a mixture of covellite and chalcocite. Much of the massive chalcocite is very pure, yielding less than 0.5% impurities upon analysis. No crystals have been observed.

The sequence relationships are shown in Table I.

Sphalerite

ZnS Isometric

Sphalerite has been reported by Berkey and Kerr¹ in the veins of the outlying mines. The writer has never been able to definitely identify this mineral at Chuquicamata.

REFERENCE. ¹ Private report, 1931. See Taylor, *op. cit.*

Covellite

CuS Hexagonal

Covellite is both a hypogene and supergene mineral at Chuquicamata and is rare as a supergene mineral in "sooty" chalcocite at Quetena. At Chuquicamata the hypogene covellite is latter than enargite in formation and was introduced following, or during, a period of fracturing. Much of it, especially in the outlying veins, shows apparent deformation, but this may be due to replacement of deformed enargite. The hypogene form is never in coarse blades as in much of the supergene material. It is widespread as both a hypogene and supergene mineral, but is never abundant. The sequence relationships are,

Supergene	<i>Late</i>	Sulphates, etc. Covellite Chalcocite Chalcopyrite
Hypogene	<i>Early</i>	Covellite Enargite

Bornite Cu_5FeS_4 Isometric

Bornite occurs at Chuquicamata as a rare mineral except in isolated points in the outlying fringe of veins at the north and east of the deposit. In these veins it occurs as a hypogene mineral replacing chalcopyrite. Subsequent to its formation, fracturing occurred and enargite was introduced, which replaced both the bornite and chalcopyrite. As a supergene mineral, bornite is very rare at Chuquicamata. It has been observed in small, sharp cubes associated with chalcocite. The age relationships of the supergene mineral are not known.

Chalcopyrite CuFeS_2 Tetragonal

Chalcopyrite is rare at Chuquicamata as both a hypogene and supergene mineral. It has been mentioned by almost everyone who has written about Chuquicamata as an important ore mineral. Actually, the hypogene variety is confined to the outer fringe of veins. It is most abundant in the northwest area, but it also occurs in veins to the north and east of the deposit, associated with bornite. It is very rare as a supergene mineral associated with chalcocite. The sequence relationships are,

Supergene	<i>Late</i>	Chalcocite, etc. Chalcopyrite
Hypogene		Enargite, etc. Bornite Chalcopyrite Molybdenite Pyrite

Pyrite FeS_2 Isometric

Pyrite is an abundant mineral at all three deposits. At Chuquicamata it occurs in grains and crystals up to one-half inch on the edge. The best crystals are found in vugs in the pyrite roots of the enargite veins. Here small brilliant cubes occur with euhedral quartz in a massive quartz-pyrite gangue.

There are several ages of pyrite at Chuquicamata, probably three and

possibly four, two or three of the pyrite periods preceding the copper sulphides. Some of the massive pyrite veins of the northeast area were comparatively free from copper mineralization and, upon weathering, have yielded abundant iron sulphates.

At Quetena and Alcaparrosa pyrite occurs as unaltered grains enclosed in sulphates. There is some associated chalcocite at Quetena that has blackened the pyrite, but at Alcaparrosa bright angular grains of pyrite occur in crystals of szolmolnokite, halotrichite and rhomboclase.

"Cupriferous pyrite" is a term commonly used in descriptions of Chuquicamata, as well as other deposits of the Andes. This is a very misleading term as many writers have pointed out.

Arsenopyrite

FeAsS Orthorhombic

The occurrence of arsenopyrite at Chuquicamata might be expected, but it has never been positively identified. One specimen of massive arsenopyrite came to the hands of the writer and was described as coming from an outlying vein. A wide search of the area failed to show any additional material, so the occurrence was never checked to the writer's satisfaction.

Tetrahedrite

Cu₃SbS₃ Isometric

Tetrahedrite was reported by Berkey and Kerr in a private report, 1931, in ores from the Panizo Vein. The writer has found specks of a gray mineral in other outlying veins, and this may be tetrahedrite but it has never been definitely identified. This unidentified mineral shows the following age relationships,

Hypogene	<i>Late</i>	Enargite
		Unknown (tetrahedrite?)
		Bornite
	<i>Early</i>	Chalcopyrite

Enargite

Cu₃AsS₄ Orthorhombic

Enargite, part of it the variety luzonite, is the primary ore mineral at Chuquicamata. It occurs as coarse bladed masses in veins up to a meter or more in width in the fringe zone and from veins of this magnitude down to disseminated grains less than a millimeter across in other parts of the deposit. There is a rough zonal distribution of the enargite as related to physical size. As one moves east from the west fissure, the enargite passes from fine-grained disseminations to larger and larger veins with less and less disseminated material. Crystals are rare and show

only the common forms. The coarsest enargite found at Chuquicamata comes from the lower levels of veins farthest to the east.

Enargite replaces pyrite, bornite and chalcopyrite and is in turn replaced by covellite and supergene sulphides and sulphates. There is a close parallel in the occurrence of enargite at Chuquicamata and Butte, Montana. In both camps the enargite occupies the central area, and chalcopyrite and bornite occur outside the main mass of the enargite.

HALOIDS

Halite and other chlorides are common in the soil throughout northern Chile. In the vicinity of these three deposits and especially at Chuquicamata where alluvium is more abundant, halite, gypsum and nitrates are found in disseminated grains, crystals and lenses. These minerals occur in the alluvium at varying depths up to several meters but usually less than a meter. There are more or less continuous openings at these depths that are lined with crystals and crystalline aggregates. The openings are roughly tabular in shape, very irregular and rarely over a foot thick. In walking over the ground, these openings give a faint drum-like sound. The origin of these salts is believed to be volcanic and the openings are probably due to solution and possibly to some extent to buckling of the superincumbent material by crystallization of the salts.

Halite

NaCl Isometric

Halite occurs widespread in the surface material about these deposits. It occurs in grains, crystals and aggregates and is found in the deposits themselves as well. The halite has been the source of the chlorine that has combined with copper to form atacamite and other chlorides so abundant in these deposits. Alcaparrosa is an exception in that only halite has been identified from there.

Bandylite

$\text{CuB}_2\text{O}_4 \cdot \text{CuCl}_2 \cdot 4\text{H}_2\text{O}$

This mineral is one of a number of new species first found by the writer in Chile, and later studied by him and others at Harvard University and the U. S. National Museum.¹

Crystallography: Tetragonal, ditetragonal-dipyramidal, $a:c = 1:0.9070$. Forms: $c(001)$, $a(010)$, $m(110)$, $d(012)$, $e(023)$, $f(011)$, $g(021)$, $o(112)$, $p(111)$, $q(221)$. Common forms: c , p , g , m . Structure cell, a_0 6.13, c_0 5.54, contains $\text{CuB}_2\text{O}_4 \cdot \text{CuCl}_2 \cdot 4\text{H}_2\text{O}$. Habit often tabular (001), frequently irregular with large pyramidal development. Cleavage (001) perfect and easy, producing thin flexible plates. $H = 2\frac{1}{2}$. $G = 2.810$. Color deep blue with greenish lights. Streak pale blue to white. Uniaxial negative, ω 1.691, ϵ 1.641. Pleochroism in blue with $\omega > \epsilon$.

ANALYSIS OF BANDYLITE			
	1	2	3
Cu	34.94	.5498	35.74
CaO	0.05		
MgO	0.05		
Na ₂ O	0.40		
K ₂ O	none		
Fe ₂ O ₃	0.35		
Cl	19.47	.5490	19.94
B ₂ O ₃	23.35	.2715	24.08
CO ₂	0.05		
H ₂ O	19.60	1.0888	20.24
Insol.	1.84		
Total	100.10		100.00

1. Mina Quetena, near Calama, Chile. Analyst, W. F. Foshag.

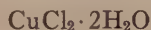
2. Molecular ratios.

3. Calculated composition for $\text{CuB}_2\text{O}_4 \cdot \text{CuCl}_2 \cdot 4\text{H}_2\text{O}$.

Occurrence: Occurs near the surface at Mina Quetena, west of Calama, Chile, associated with antofagastite and atacamite on rusty quartz.

REFERENCE. ¹ Palache and Foshag, *Am. Mineral.*, vol. 23, p. 85, 1938.

*Antofagastite*¹



The natural occurrence of this common laboratory product was first found by the writer.

Orthorhombic, dipyramidal, $a:b:c = 0.9177:1:0.4631$.¹ Forms:² $c(001)$, $b(010)$, $a(100)$, $m(110)$, $t(520)$, $q(103)$, $r(101)$, $s(301)$, $p(111)$. Common forms: b , m , t . Structure cell: a_0 7.38, b_0 8.04, c_0 3.72, contains $\text{Cu}_2\text{Cl}_4 \cdot 4\text{H}_2\text{O}$.³ Crystals commonly curved. Cleavage $m(110)$ perfect, $c(001)$ good. Brittle. Fracture conchoidal. $H = 2\frac{1}{2}$. $G = 2.4$. Color bluish green to greenish blue with sometimes a yellowish tinge.

Biaxial positive, $2V = 75^\circ$, $r < v$; $\alpha = b = 1.646 = \text{bright green}$, $\beta = c = 1.685 = \text{olive green}$, $\gamma = 1.745 = \text{pale blue}$.

Analysis	1.	2.
Cu	36.89	37.22
Fe ₂ O ₃	0.20	
CaO	0.15	
MgO	0.04	
Cl	40.68	41.52
H ₂ O	20.81	21.26
Insol.	0.95	
Total	99.72	100.00

1. Mina Quetena, Calama, Antofagasta, Chile. W. F. Foshag, analyst.

2. Composition for $\text{CuCl}_2 \cdot 2\text{H}_2\text{O}$.

Occurrence: Found near the surface at Mina Quetena, west of Calama, Chile, associated with bandylite and atacamite. These chlorides occur in a leached zone above the massive iron sulphates.

Copper chlorides are rare in nature, atacamite and the rare chloride nantokite being the only ones known heretofore. As stated above, at Quetena this new chloride is associated with atacamite and the new copper borate-chloride bandylite. Antofagastite was the first mineral to form, followed by bandylite, with atacamite last. In the mine these minerals are associated with heavily iron-stained vuggy quartz veins. Antofagastite extends to the greatest depths, while abundant atacamite occurs within a foot of the surface and decreases in amount with depth. The sequence relationships of the three minerals are very clear in the field.

REFERENCES. ¹ Palache and Foshag, *Am. Mineral.*, vol. 23, p. 85, 1938.

² Forms (100) (103) (101) on artificial crystals only. See Groth, *Chem. Krist.*, vol. 1, p. 238, 1906.

³ Harker, *Zeits. Krist.*, vol. 93, p. 136, 1936.

Atacamite



Orthorhombic, dipyramidal— $2/m \ 2/m \ 2/m$, $a:b:c=0.6617:1:0.7535$,¹
 $p_0:q_0:r_0=1.1387:0.7535:1$.

New Forms	No. of Crystals	Measured		Calculated	
		ϕ	ρ	ϕ	ρ
370	3	32°37'	90°00'	32°56'	90°00'
012	1	0 38	19 30	0 00	20 39
0.11.2	1	0 00	76 27	0 00	76 26
553	2	56 34	66 19	56 30½	66 17
232	2	47 07	58 12	45 13	58 04
143	2	21 14	47 15	20 42	47 02

Much of the atacamite at Chuquicamata and all the atacamite at Quetena occurs in long acicular crystals or in crystalline mats and radiating rosettes of prismatic crystals. A common habit at Chuquicamata is tabular, enormously extended on {010}. Strong vicinal development sometimes gives the crystals an axe-like shape.

Occurrence: At Chuquicamata atacamite is limited to the upper one hundred feet of the deposit. While erratic in its distribution, it is most commonly found, in quantity, in the upper portions of the more massive sulphide veins. It occurs in a pulverent maroon-colored iron-oxide matrix in the axe-like crystals and less commonly in matted masses of minute prismatic crystals. As a rule it occurs in areas that might be

called "low acid" as contrasted with the sulphate-rich or "high acid" areas; certainly it forms in areas of too low acidity to produce antlerite.

The place of atacamite in the general sequence is not clear, but its relations to a few associated minerals are definite. A common association is kroehnkite-atacamite-natrochalcite, named in order of formation from oldest to youngest. Kroehnkite is a normal hydrous mineral, while the other two are basic. The relationship of atacamite to the two other minerals is very intimate and there is considerable overlap in the periods of formation, with distinctly separate periods for kroehnkite and natrochalcite. Veinlets of atacamite cut turquoise at Chuquicamata and crystals occur on crystals of leightonite. It is commonly associated with chrysocolla and is always the earlier mineral.

At Quetena atacamite occurs with antofagastite and bandylite and is the youngest mineral of the three. It is limited to the upper twenty feet of the deposit now exposed. In all of these associations atacamite agrees with the general sequence outlined in Table I, but the gaps between some of the associated minerals may be so great that it is impossible to say with certainty that it always conforms to this sequence.

REFERENCE. ¹ Ungemach, *Bull. Soc. Min. France*, vol. 34, p. 148, 1911.

OXIDES

Opal

$\text{SiO}_2 \cdot n\text{H}_2\text{O}$ Amorphous

Opal occurs at Chuquicamata only in association with chrysocolla. It apparently results from the lack of sufficient copper to form chrysocolla, as it occurs coating this mineral and grades into it. This relationship might be expected from the composition of the two minerals.

Cuprite

Cu_2O Isometric, plagiohedral

Cuprite occurs in a number of associations at Chuquicamata. Fibrous cuprite occurs after antlerite. The cuprite preserves the structure of the antlerite even to the chatoyance. Massive and crystalline cuprite occur after native copper. The crystals are simple cubes showing small octahedral and dodecahedral faces. The massive cuprite replaces copper and is commonly associated with "copper pitch." Cuprite is a rare mineral at Chuquicamata, occurring in the "low acid" areas about the central part of the deposit. It is most common along the east-central and south-east areas and in the northwest area. Fine specimens have been obtained from the veins outside the deposit to the northeast.

卷之四

一、政治：政治は、国家の内外の関係を調整し、社会の秩序を維持するための活動である。政治は、国家の権威を行使し、社会の利益を追求するための活動である。政治は、国家の内外の関係を調整し、社会の秩序を維持するための活動である。政治は、国家の権威を行使し、社会の利益を追求するための活動である。

11/11/11

[The page contains approximately 20 horizontal lines of handwritten Japanese cursive script.]

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"Limonite"

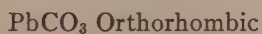
Under the term "limonite" a number of iron oxides at Chuquicamata may be mentioned here. It is possible, in the field to differentiate the type of iron oxide formed through the oxidation of pyrite, high-grade copper ore, hematite, etc. These are given various names referring to the color of the oxide. The exact nature of these oxides has never been determined.

Many beautiful specimens of iridescent limonite have come from Chuquicamata, some in delicate imitative shapes of considerable beauty. An unusual form of iridescent limonite is that formed after gypsum. The gypsum commonly weathers to stringy stalactitic masses, and when this material is replaced by limonite it results in very striking and beautiful material.

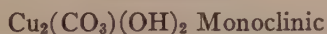
CARBONATES

Dolomite

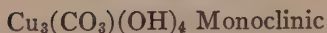
The veins in the northwest area carry some carbonate as a gangue. The material is very fine grained and it has never been definitely determined. An analysis showed it to consist of calcium and magnesium carbonate in somewhat varying proportions, the variability being too great for dolomite. It is probably a mixture of dolomite and calcite. Due to the rarity of magnesite in ore veins, it is doubtful if it is a mixture of magnesite and calcite.

Cerussite

Cerussite is the only lead mineral that has ever been identified at Chuquicamata. Lead minerals are unknown in the other deposits. The cerussite occurs in rare pockets in the central northwest area of the mine. The crystals range in size up to three millimeters and are associated with antlerite in fibrous masses. The antlerite is later than the cerussite. Due to the deep etching, the crystals were not measured.

Malachite

Malachite is rare at Chuquicamata. One specimen was found in the southeast area of the deposit where the fibrous malachite was later than associated brochantite and earlier than associated azurite. Malachite, as well as all the other carbonates with the exception of cerussite, occurs in areas of "low acidity."

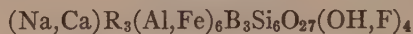
Azurite

Azurite occurs as a late mineral in the Mina Flor de Bosque at Chuquicamata. The associated minerals and the sequence relationships are,

<i>Late</i>		Chrysocolla
		Azurite
		Malachite
	Supergene	Brochantite
<i>Early</i>	Hypogene	Specularite

SILICATES

The rock-forming silicates will not be considered here. Only the unusual silicates, tourmaline and chrysocolla, will be mentioned.

Tourmaline

Rhombohedral, hemimorphic

Tourmaline occurs in two forms at Chuquicamata. It is common near the roof of the batholith to the west of the deposit in minute radiating needles filling cracks in the granodiorite. Some of the minor veins of copper near the central part of the batholith, also near the roof, carry tourmaline as a vein mineral. Some of these veins are quite large, but the mineralization is weak and spotty.

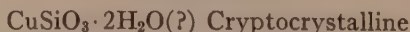
To the north and west of the deposit in the country rock about the batholith, pegmatites of albite-tourmaline-titanite occur. The tourmaline is black to deep blue and replaces the albite. Rough crystals four inches in diameter can be found. The indices of the tourmaline are,

ω —dark brownish green—1.667

ϵ —light reddish brown—1.638

These indices would indicate a tourmaline with an iron oxide content of about 13%.¹

REFERENCE. ¹ Ward, *Am. Mineral.*, vol. 16, p. 145, 1931.

Chrysocolla

There are evidently a number of minerals that have been called chrysocolla and are hard to distinguish. There are at least three different minerals in the "chrysocolla" at Chuquicamata with different optical properties. It would be impossible to separate them and they never occur pure. These are all included here under the term chrysocolla.

The chrysocolla occurs in botryoidal, cryptocrystalline masses in the extreme southeast portion of the deposit. The area is a "low acid" one and the most commonly associated mineral is atacamite, an earlier mineral. In some of the open vugs the chrysocolla grades into opal.

Sphene

CaTiSiO_5 Monoclinic

Sphene occurs in the tourmaline-albite-titanite pegmatites to the north of the deposit at Chuquicamata. It is in small, brilliant cinnamon-brown crystals rounded and etched. It would appear that the sequence in the pegmatite was,

<i>Late</i>	Tourmaline
	Titanite
<i>Early</i>	Albite

ARSENATES-PHOSPHATES

Chenevixite

$\text{Cu}_2\text{Fe}_2(\text{AsO}_4)_2(\text{OH})_4 \cdot \text{H}_2\text{O}$

A mineral tentatively identified¹ as this species has recently been found at Chuquicamata, associated with enargite in the upper portions of the deposit. Crystals were not found. It is interesting chiefly as the only evidence yet found of the oxidation of enargite. Arsenates might well be expected to occur in abundance and variety.

REFERENCE. ¹ An analysis by the chemist of the Company showed a similarity with published analyses of chenevixite.

Turquoise

$\text{CuO} \cdot 3\text{Al}_2\text{O}_3 \cdot 2\text{P}_2\text{O}_5 \cdot 9\text{H}_2\text{O}$ Triclinic

Turquoise was first identified at Chuquicamata in 1931 by the writer. It is rather common but is characteristically associated with the areas of "low acid," along the eastern side and at the northern end of the mine. It is almost always associated with specular hematite. The finest quality is a deep blue equal to the Persian material and can be cut and polished. From this deep blue, dense material it grades to an almost colorless, pulverent variety. Atacamite and antlerite are commonly associated with it, always later. At first the writer thought the mineral was primary, but now he believes it to be supergene. The source of the phosphorus is unknown. There is a large amount of phosphorus fixed in the turquoise. It is difficult to believe that this amount could have been derived from the alteration of apatite in the altered granodiorite, the source postulated by Pogue.¹ Boman² has described turquoise from both Calama and Antofagasta in beads.

REFERENCES. ¹ Pogue, *Mem. Nat. Ac. Sci.*, vol. 12, 1915.

² Boman, *Antiquites de la Region Andine de la Republique Argentine et du desert d'Atacama*, 1902, p. 766.

NITRATES

Soda Niter

NaNO_3 Rhombohedral

Soda niter occurs in massive aggregates in the upper portion of the deposit at Chuquicamata and in the alluvium surrounding all three deposits. Associated minerals are atacamite, bloedite and altered mirabilite. No sequence relationships can be given for these minerals. The soda niter is certainly earlier than the bloedite in specimens examined by the writer. The mineral is believed to be of volcanic origin.

BORATES

Ulexite

$\text{NaCaB}_5\text{O}_9 \cdot 8\text{H}_2\text{O}$ Monoclinic

Ulexite has been identified in the alluvium at Chuquicamata. It occurs associated with gypsum and halite in loose masses of fine silky fibers. Borax may also be present but it has never been positively identified. The borate-chloride bandylite, from Mina Quetena, is the only other boron-bearing mineral reported.

SULPHATES

Thenardite

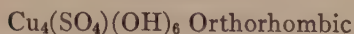
Na_2SO_4 Orthorhombic

Thenardite occurs at Chuquicamata and Alcaparrosa as an alteration product of mirabilite. It has never been observed at Quetena. The mineral occurs as a fine-grained white powder. In northern Chile this mineral occurs in beds on the east side of the Central Valley, near Iquique. Many writers have noted it from this district. The total volume of the mineral is small. It is always a late, near-surface mineral, pseudomorphic after mirabilite.

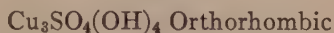
Anhydrite

CaSO_4 Orthorhombic

Anhydrite occurs in the alluvium about Chuquicamata and, rarely at Quetena, associated with gypsum, halite and soda niter. It is not a common mineral, although it occurs in thick beds in the valley of the Rio Loa in the vicinity of these deposits.

Brochantite

Brochantite is a comparatively rare mineral in the ore at Chuquicamata and Quetena. For many years the main ore mineral at Chuquicamata was called brochantite, but various people have studied the ore in laboratories and it has been recognized for some time that antlerite and not brochantite is the main ore-mineral. Brochantite occurs about the borders of the deposit in areas where the minerals formed from dilute solutions carrying a relatively small percentage of acid. Associated minerals are gypsum and chrysocolla. As stated before, brochantite is an early mineral, earlier than the rare malachite with which it may be associated. Another occurrence at Chuicamata is in the veins of the northwest area. These veins carry primary carbonates in the gangue. Brochantite is later than gypsum at Quetena.

Antlerite

It has been known for some time that the main ore mineral at Chuquicamata was not brochantite but antlerite.¹ The crystallography of antlerite has been studied by Professor Palache and the orientation changed from that of Ungemach² to conform to the orientation of brochantite and atacamite. Several new forms were observed on the crystals from Chuquicamata by Ungemach. Besides occurring as implanted crystals, antlerite forms well-defined cross-fibre veins cutting silicified rock.

Antlerite is the last step in the copper mineralization at Chuquicamata and a late mineral in the supergene sequence. Its place in the sequence may be seen in Table I A2 and A3. The vertical range of the mineral is great, ranging to depths of 1,000 feet. It usually forms as an oxidation product of chalcocite and covellite.

Several minerals have been described from Chile under different names that are actually varieties of antlerite. Stelznerite³ and heterobrochantite⁴ belong here.

REFERENCES. ¹ Andrieth and Martens, *Am. Mineral.*, vol. 10, p. 161, 1925.

² Ungemach, *Bull. Soc. Min.*, vol. 47, p. 1, 1924.

³ Thadeeff, *Zeits. Krist.*, vol. 31, p. 242, 1899.

⁴ Buttgenbach, *Bull. Soc. Geol. Belg.*, vol. 41, B 164, 1926.

Mirabilite

Mirabilite is common but spotty in occurrence in the upper portion of the deposit at Chuquicamata. It has not been observed at depths

greater than 60 feet, although it probably extends deeper than this. It has not been observed at Alcaparrosa and was only identified from its alteration product, a dehydration form, thenardite. The water in mirabilite is loosely held and goes off at 32.4°C .¹ In the arid climate of the Atacama desert, freshly broken surfaces of mirabilite have been studied and it was found that it required twenty seconds for a film of dull white thenardite, Na_2SO_4 , to form over the mirabilite.

Mirabilite is difficult to place in the sequence at Chuquicamata and Alcaparrosa. At the former it is associated only with bloedite and occurs in the upper portions of the deposit. It is probably a late mineral and formed after the soluble iron sulphates had moved downward to lower levels. At Chuquicamata it occurs exclusively in the sericitic rock along the western side of the deposit. At Alcaparrosa it occurs with soda niter near the surface.

REFERENCE. ¹ Wuite, *Zeits. phys. Chem.*, vol. 86, p. 249, 1914.

Szomolnokite



This mineral was first observed in 1891 by Krenner,¹ who named it from the type locality, Szomolnok, Hungary. Mackintosh² had, however, in 1889 analyzed an impure sample of the same mineral from Chile, but did not name it. In 1903 Scharizer³ analyzed pure szomolnokite associated with roemerite from Chile and erroneously named it "ferropalidite." In 1928 Krenner's posthumous paper by Zimanyi⁴ gave an analysis of material from the type locality, and a crystallographic discussion. Schaller⁵ later studied crystals from Utah and found that his data did not check well with Krenner's. The writer and others in the Harvard laboratory have again investigated the crystallography of this mineral, and have corrected Krenner's work. It was found that the positive and negative quadrants of Krenner are reversed from their proper position. Accordingly, Krenner's crystal has been redrawn (Fig. 4a), and a crystal of the Alcaparrosa szomolnokite with a very different habit is also given (Fig. 4b). This unusual habit, tabular (111), is very much like that of lazulite from Grave's Mountain, Georgia.

Since the habit of the crystals was so unusual it was thought at first that they were triclinic. However, the decisive measurement which established the true symmetry of the crystal was made by Professor Palache, who measured a crystal with [010] polar, that is, in the position of the second permutation. As neither pinacoid was present, the adjustment was made by using two pairs of faces of the forms (111) and ($\bar{1}\bar{1}\bar{1}$).

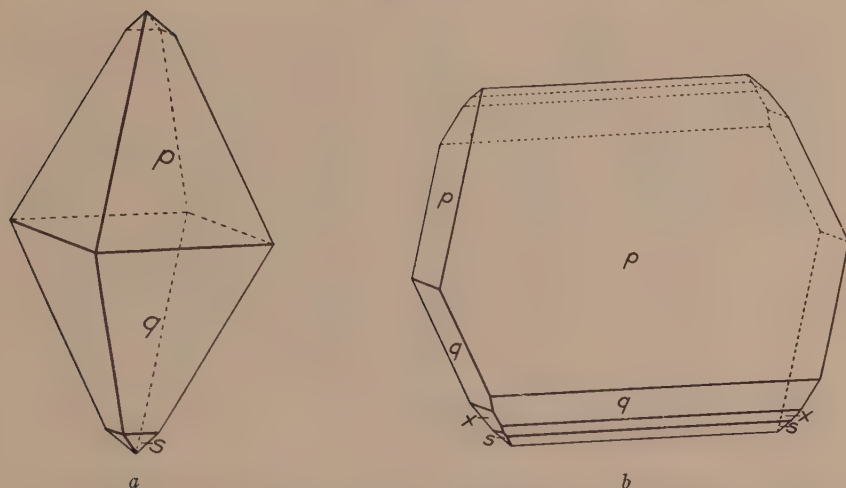


FIG. 4. Crystals of Szomolnokite.

The following table gives some of the measured and calculated values for the more prominent forms found in this study.

Form	No. of Observations	Measured		Calculated	
		ϕ	ρ	ϕ	ρ
$m(110)$	3	$46^{\circ}43'$	$90^{\circ}00'$	$46^{\circ}57'$	$90^{\circ}00'$
$t(012)$	3	1 18	42 10	1 31	42 08
$s(\bar{1}13)$	22	$-45\ 31$	40 35	$-45\ 35\frac{1}{2}$	$40\ 44\frac{1}{2}$
$x(\bar{1}12)$	20	$-45\ 55$	52 30	$-45\ 58$	52 27
$p(111)$	28	$47\ 02\frac{1}{2}$	$69\ 21\frac{1}{2}$	$47\ 02\frac{1}{2}$	$69\ 21\frac{1}{2}$
$q(\bar{1}11)$	28	$-46\ 19\frac{1}{2}$	69 06	$-46\ 19\frac{1}{2}$	69 06

An angle table for the species has been prepared by Professor Palache. In this table the new forms found by Dr. Schaller, as yet unpublished, are given, with his permission,* as well as the new forms found in the Harvard laboratory.

Monoclinic; prismatic— $2/m$

$$\begin{aligned}
 a:b:c &= 0.9344:1:1.8085 & \beta &= 91^{\circ}22\frac{1}{2}' \\
 p_0:q_0:r_0 &= 1.9356:1.8080:1 & \mu &= 88^{\circ}37\frac{1}{2}' \\
 r_2:p_2:q_2 &= 0.5531:1.0706:1 \\
 p_0' &= 1.9184, \quad q_0' = 1.8085, \quad x_0' = 0.0240
 \end{aligned}$$

* The angles of this table agree well with those observed by Schaller. Personal communication.

Forms	ϕ	ρ	ϕ_2	$\rho_2=B$	C	A
<i>b</i> * 010	0°00'	90°00'	0°00'	0°00'	90°00'	90°00'
<i>m</i> 110	46 57	90 00	0 00	46 57	88 59½	43 03
<i>i</i> † 012	1 31	42 08	88 37½	47 53	42 07	88 59
<i>u</i> * 023	1 08½	50 20	88 37½	39 41	50 19	89 07½
<i>s</i> 113	-45 35½	40 44½	121 36½	62 49½	41 44½	152 12½
<i>x</i> † 112	-45 58	52 27	133 05	56 33½	54 09½	145 15
<i>n</i> † 223	-46 08½	60 07	141 27	53 04½	61 07	141 08
<i>p</i> 111	47 02½	69 21½	27 14½	50 23	68 21	46 46½
<i>q</i> 111	-46 19½	69 06	152 10½	49 49½	70 06	132 30½
<i>z</i> † 137	-17 52½	39 09½	104 02	53 03	39 36	101 10½
<i>w</i> † 131	19 42	80 09½	27 14½	21 56	79 50½	70 36

* New forms, Schaller. † New forms, Bandy.

Habit: Pyramidal crystals, commonly distorted, tabular parallel to (111); parallel growth common.

Twinning: Twinning common, but twin laws not determined in this study.

Physical Properties: Fracture conchoidal, brittle. $G=3.05$. $H=2\frac{1}{2}$. Luster vitreous. Color, light shades of yellow, blue, red, brown, colorless.

Optical Properties:

n	Positive
$\alpha=1.591$	$Y=b$
$\beta=1.623$	$X \wedge c = -26^\circ$
$\gamma=1.663$	$2V=80^\circ$
	$r > v$, strong

Composition: hydrous ferrous sulphate, $\text{FeSO}_4 \cdot \text{H}_2\text{O}$.

Pyrognostics: B.B. light brown. Closed tube, yields acid water and black residue. Slowly soluble in water, yields brown solution.

Occurrence: Commonly associated with pyrite. Rare at Quetena. Szomolnokite apparently forms under arid conditions from solutions of high acid content and of high concentration. At Quetena it is intimately associated with halotrichite, a mineral to which it apparently alters. At Alcaparrosa it alters to roemerite and to rhomboclase. It is apparently the first mineral to form upon oxidation of pyrite, where there is no abundance of oxygen. With abundant oxygenated water, pyrite probably alters first to rhomboclase.

Relation to Kieserite: The new axial ratio here given for szomolnokite shows its close relationship to the corresponding magnesium mineral, kieserite.

	<i>a</i>	<i>b</i>	<i>c</i>	β
Kieserite	0.9147	1	1.7445	91°07'
Szomolnokite	0.9344	1	1.8085	91 23

The crystals of kieserite are similar to those of szomolnokite from the type locality. The optical orientation in the two minerals is likewise similar. No intermediate compositions have been recorded, however.

REFERENCES. ¹ Krenner, *Ak. Ertesitő, Budapest*, vol. 2, p. 96, 1891.

² Mackintosh, *Am. Jour. Sci.*, vol. 38, p. 245, 1889.

³ Scharizer, *Zeits. Krist.*, vol. 37, p. 547, 1903.

⁴ Zimanyi, *Centralb. Min.*, A, p. 268, 1928.

⁵ W. T. Schaller, *U. S. Geol. Survey*, unpublished.

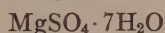
Gypsum



Gypsum is a common mineral in the alluvium about these deposits and occurs within the deposits themselves to some extent. In the alluvium the gypsum occurs in beds up to a foot or more in thickness. The beds are usually made up of fibrous gypsum, although rarely crystals have been found. In some of the old mines about the Chuquicamata deposit the walls of the workings may be coated with gypsum in curved forms. Commonly at Chuquicamata the gypsum is stained deep blue by copper sulphate. In the alluvium much of the gypsum is stained red with iron oxide.

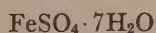
The only sequence relationship that could be established showed the gypsum to be earlier than either antlerite or brochantite. Further to the east, in the Cerros de Sal, beds of coarse crystals of gypsum several yards thick overlie a thick bed of halite.

Epsomite



Epsomite occurs associated with other salts in the alluvium about the deposits. Further to the west, beds of epsomite four to eight inches thick are associated with pickeringite. About the deposits the epsomite is in white pulverent masses, commonly fibrous.

Melanterite



Melanterite has been reported from Alcaparrosa¹ associated with roemerite. This mineral was not encountered in this study, and there is a possibility that Frenzel confused fibroferrite with melanterite.

REFERENCE. ¹ Frenzel, *Min. Mitt.*, vol. 11, p. 221, 1890.

Pisante (Salvadorite)

The material described from Quetena¹ and called *salvadorite* differs in no important respect from pisanite, the iron-copper member of the melanterite group.² The following analyses show about a per cent more copper than that found in the original pisanite.

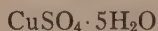
	1	2
FeO	8.49	9.59
CuO	18.77	17.57
SO ₃	27.87	28.16
H ₂ O	44.65	44.31
Total	99.78	99.63

1. Blue "salvadorite." 2. Green "salvadorite." 1-2 Herz, analyst.

Pisanite is a late mineral at Quetena forming, as a rule, after the iron sulphates have crystallized. This sequence is conformable with data obtained from the studies of the formation of artificial sulphates.

REFERENCES. ¹ Herz, *Zeits. Krist.*, vol. 17, p. 26, 1896 gave a prism measurement of $48^\circ 16'$, which is the complementary angle for the prism angle of pisanite.

² Powder photographs of melanterite and pisanite are not similar and a series probably does not exist between the two minerals. Boothite is the pure copper member of the group.

Chalcanthite

Chalcanthite is abundant at Chuquicamata and uncommon at Quetena today, although in years past it was an important ore mineral. At Chuquicamata it occurs in cross-fibre veins up to two inches wide. Occasionally vugs lined with crystals of chalcanthite are found, and small crystals are not rare in the north area of the deposit. A number of these crystals were measured and two new forms were observed.*

	Measured		Calculated		No. of Faces
	ϕ	ρ	ϕ	ρ	
<i>e</i> (121)	$52^\circ 25'$	$59^\circ 28'$	$52^\circ 28'$	$59^\circ 19'$	1
<i>h</i> (122)	$-153\ 30$	$23\ 49$	$-153\ 33$	$23\ 53\frac{1}{2}$	1

Chalcanthite occurs as both an early and a late mineral. At Chuquicamata one of the first sulphates to form from chalcocite is chalcanthite, closely followed in time by kroehnkite. It is apparent that these sulphates do not form from solutions carrying a high percentage of iron

* Elements of Tutton in the orientation of Kupfer.

sulphate, and thus form after much of the iron sulphate has been precipitated. It occurs in the upper portions of the "mixed ore" zone at Chuquicamata, a zone carrying both chalcocite and sulphates. Chalcanthite has not been definitely identified at Quetena, due to the difficulty of separating it from pisanite.

Bloedite



Bloedite is a common mineral at Chuquicamata and rare at the other deposits. At Chuquicamata it occurs most abundantly in the southwest area of the deposit and is limited to the upper 75 feet. It is usually in fibrous or granular veins and crusts. Crystals of good quality have never been observed. The common associated mineral is mirabilite or its dehydration product thenardite. Soda niter has been found with it, and atacamite is not rare in this association. It is often replaced by kroehnkite and leightonite. The age relationships with mirabilite and soda niter are not clear, but it is probably later than mirabilite. At Quetena it was observed in a crust, replaced by jarosite and replacing voltaite and coquimbite.

Picromerite

A mineral identified as picromerite on the basis of optical properties occurs in all three deposits. The indices of the material from Quetena were: $\alpha = 1.462$, $\beta = 1.464$, $\gamma = 1.471$; $r > v$; 2V large. The indices varied in the other deposits.

Picromerite occurs in white crusts of glistening crystals. It has the appearance of a mineral that has resulted from dehydration. There are several other white minerals of similar appearance found in these deposits, and some show minute and complex twinning.

At Chuquicamata this mineral is rather widespread, occurring most commonly with hohmannite, also with metavoltine and metasideronatriite. At Quetena it is commonly associated with botryogen and at Alcaparrosa with alums and massive pickeringite.

Leightonite



This mineral, long known to the geological staff at Chuquicamata, has been recently described by Palache.¹ The following abstract of its properties is taken from his paper.

Pseudo-orthorhombic (triclinic)

$$a:b:c=0.7043:1:0.4578; p_0:q_0:r_0=0.6500:0.4578:1$$

Forms	ϕ	ρ
<i>b</i> 010	0°00'	90°00'
<i>a</i> 100	90 00	90 00
<i>n</i> 130	25 19½	90 00
<i>m</i> 110	54 50½	90 00
<i>d</i> 031	0 00	53 56½
<i>e</i> 101	90 00	33 01½
<i>p</i> 111	54 50½	38 29
<i>q</i> 131	25 19½	56 39

The crystals are too poor for details of the triclinic form elements to be determined, but the nature of the lamellar twinning and optical properties make it certain that leightonite is triclinic. Twinning is probably parallel to (010) and (100) of the triclinic setting.

Peacock² was able to show that by a new setting of the triclinic mineral polyhalite, a homologue of leightonite, a close parallelism in the form of the two minerals became evident:



Triclinic: $a:b:c=0.7176:1:0.4657$

$$\alpha=91^\circ39', \beta=90^\circ06\frac{1}{2}', \gamma=91^\circ53'$$



Pseudo-orthorhombic: $a:b:c=0.7043:1:0.4578$

$$\alpha=90^\circ, \beta=90^\circ, \gamma=90^\circ$$

Habit: Prismatic in flattened blades [001] the crystals commonly showing some curvature of macrodome faces, producing an hourglass-like appearance. It also forms cross-fibre veins up to one-half inch in width with kroehnkite and bloedite. The crystals reach a maximum length of 1 centimeter, generally much smaller.

Physical properties: No cleavage. Glassy fracture. $H=3$. $G=2.95$ (Berman).

Optical properties: (Berman) Color faintly blue to bluish green, transparent.

$$\begin{array}{l} n(\text{Na}) \\ \alpha=1.578 \\ \beta=1.587 \\ \gamma=1.595 \end{array} \left. \vphantom{\begin{array}{l} n(\text{Na}) \\ \alpha=1.578 \\ \beta=1.587 \\ \gamma=1.595 \end{array}} \right\} \text{all } \pm .002$$

Biaxial negative

$$2V=65^\circ$$

$r > v$ fairly strong

Extinction about 2° to

Y on sections parallel to (010)

Chemical composition:

ANALYSES BY F. A. GONYER

	1. Crystals	2. Massive	Calculated for the Formula $K_2Ca_2Cu(SO_4)_4 \cdot 2H_2O$
CuO	11.97	11.24	12.36
K ₂ O	13.93	13.62	14.66
Na ₂ O	0.56	0.98	
CaO	18.41	17.50	17.44
SO ₃	49.33	50.75	49.92
H ₂ O	5.71	5.98	5.62
Total	99.91	100.07	100.00

Occurrence: As bladed crystals on fractured rock surfaces and in cross-fibre veins. The following notes on the distribution of leightonite in the mine at Chuquicamata are taken from a letter written by O. W. Jarrell, a geologist on the mine staff. Leightonite occurs quite abundantly on the east and west sides of the open pit near the south end. It is limited to within about fifty yards of the original surface, below which it is not found. Thus it is nowhere found in the center of the present pit. Minerals found with it are chiefly atacamite and kroehnkite, never antlerite. It was found only under conditions of low acidity and hence is found generally in borderland material, never in rich ore.

Name: Leightonite is named in honor of Dr. Tomas Leighton, Professor of Mineralogy at the University of Santiago, Chile.

REFERENCES. ¹ Palache, *Am. Mineral.*, vol. 23, p. 34, 1938.

² Peacock, *Am. Mineral.*, vol. 23, p. 38, 1938.

ALUM AND HALOTRICHITE GROUPS

These groups are considered together because of their chemical similarity. The so-called isometric alums are usually inverted to lower symmetry forms, and the crystals now found are therefore pseudomorphs.

Isometric	Kalinite	$K_2Al_2(SO_4)_4 \cdot 24H_2O$
	Mendozite	$Na_2Al_2(SO_4)_4 \cdot 24H_2O$
	Mineral 42	Unknown
Monoclinic	Tamarugite	$Na_2Al_2(SO_4)_4 \cdot 12H_2O$
	Pickeringite	$MgAl_2(SO_4)_4 \cdot 22H_2O$
	Halotrichite	$FeAl_2(SO_4)_4 \cdot 22H_2O$

Kalinite (Potash Alum)

The mineral from Chuquicamata identified here as kalinite is isotropic with a refractive index of 1.455 and was not found in crystals. No biaxial

material was identified as kalinite or potash alum. This mineral is one of the few potash-bearing minerals to be found at Chuquicamata. It occurs there as a late mineral, later than natrojarosite and other iron sulphates. It is confined to the upper fifty feet of the deposit.

The mineral is much more abundant at Quetena. There it occurs with pisanite and jarosite. It forms both earlier and later than jarosite but is later than other copper and iron sulphates. Kalinite from there is always biaxial and varies somewhat from the indices given.¹

REFERENCE. ¹ Larsen and Berman, *Bull.* **848**, *U. S. Geol. Survey*.

Mendozite (Soda Alum)



At Alcaparrosa and Chuquicamata, mendozite occurs in some abundance, and it is common at Quetena. In all of these places it is not isotropic,¹ and the white plates appear under the microscope as complex twins. The following optical data were obtained:

$$\beta = 1.466, \gamma = 1.472, X = b, Z \wedge \text{twin plane} = 40^\circ$$

Biaxial negative

Mendozite is a late mineral in the sequence and occurs after alunogen, with which it is easily confused. The sequence at Alcaparrosa is,

<i>Late</i>	Fibroferrite
	Mineral 42
	Tamarugite
	Mendozite
	Pickeringite
	Copiapite
<i>Early</i>	Metavoltine

The mineral occurs throughout the deposit but no crystals were observed.

REFERENCES. ¹ Dana (p. 951) states that the mineral often exhibits anomalous double refraction.

Mineral 42

This mineral occurs at Alcaparrosa as tiny brilliant yellow, transparent crystals with well-developed faces conformable with isometric symmetry, but an optical examination revealed an inversion, so that the crystals are now made up of anisotropic aggregates. The forms found include the cube, dodecahedron, trapezohedron, and the octahedron, the latter in excellent faces.

$H = 2\frac{1}{2}$, $G = 1.80$. Only the mean refractive index (1.583 to 1.588) was determined, since the biaxial segments were too small to make a com-

plete optical study possible. The axial angle is large, and abnormal interference colors were visible.

The mineral occurs along the contact of tamarugite and the iron sulphates, metavoltine and copiapite. If it is an alum, it may be a soda-iron member.

The sequence is,

<i>Late</i>	Fibroferrite
	Mineral 42
	Tamarugite
<i>Early</i>	Mendozite

Tamarugite



Tamarugite was originally described from northern Chile,¹ and later again analyzed from Chile.² The mineral has been analyzed from St. Bartholomew,³ Grotto del Zolfo⁴ and Gascogne River, Australia.⁵ Since the agreement between the analyses is good, the species seems well established.⁶

	ANALYSES		
	1	2	3
Na ₂ O	9.04	8.64	8.86
CaO	0.20		
Al ₂ O ₃	14.48	14.66	14.58
SO ₃	45.66	45.48	45.70
Cl	0.12	0.48	
H ₂ O	30.86	31.40	30.86
Total	99.36	100.66	100.00

1. Iquique, Northern Chile. Schulze, anal.¹

2. Grotto del Zolfo, Cap Miseno. Zambonini, anal.⁴ Includes 1.12% hygroscopic water.

3. Theoretical composition for Na₂Al₂(SO₄)₄ · 12H₂O.

The optical properties determined on material from the three deposits of this study are slightly variable and differ somewhat from the values given in the literature.⁷ One set of observations gives:

$$\begin{aligned} \text{Biaxial positive } 2V &= 60^\circ \\ \alpha &= 1.488, \beta = 1.491, \gamma = 1.500 \end{aligned}$$

Tamarugite occurs associated with various alums and is always a late mineral, usually later than the alums.

REFERENCES. ¹ Schulze, *Verh. Naturw. Deutsch. Ver. Santiago*, vol. 2, p. 56, 1889.

² Domeyko, *Mineralogia*, 2nd App., p. 30, 1883.

³ Cleve, *Svenska Vet. Ak. Handlingar*, vol. 9, p. 12, 1870.

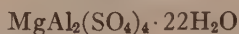
⁴ Zambonini, *Ac. Sc. Napoli, Rend.*, Dec. 1907.

⁵ Simpson *J. Roy. Soc. Western Australia*, vol. 9, p. 62, 1923.

⁶ The species has been omitted from recent editions of Ford's Dana Textbook of Mineralogy.

⁷ Larsen and Berman, *Bull.* 848, *U. S. Geol. Surv.*

Pickeringite



Hitherto nothing was known with certainty as to the crystallography of this mineral. The data contained in the following tables are therefore new and are based on the measurement of many crystals. These were slender needles (Fig. 5) and the terminal faces were excessively small, but the data are well established and the crystal setting is confirmed by an x -ray study.

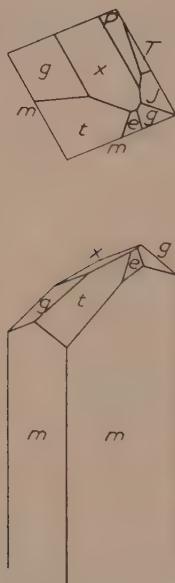


FIG. 5. Crystal of Pickeringite.

TABLE 1. ANGLE TABLE—PICKERINGITE

Monoclinic

$a:b:c=0.8655:1:0.2551$	$\beta=96^{\circ}33\frac{1}{2}'$
$p_0:q_0:r_0=0.2948:0.2534:1$	$\mu=83^{\circ}26'$
$r_2:p_2:q_2=3.9459:1.1638:1$	
$p_0'=0.2967, q_0'=0.2551, x_0'=0.1150$	

Forms	ϕ	ρ	ϕ_2	$\rho_2 = B$	C	A
<i>b</i> 010	0°00'	90°00'	—	0°00'	90°00'	90°00'
<i>a</i> 100	90 00	90 00	0°00'	90 00	83 26½	0 00
<i>m</i> 110	49 18½	90 00	0 00	49 18½	85 02	40 41½
<i>n</i> 210	63 26	90 00	0 00	63 26	84 08½	26 34
<i>w</i> 011	24 16	15 38	83 26½	75 46½	14 13½	83 38½
<i>x</i> 021	12 42	27 36½	83 26½	63 07½	26 52½	84 09
<i>y</i> 031	8 33	37 44	83 26½	52 45½	37 14½	84 47
<i>z</i> 041	6 26	45 45½	83 26½	44 36½	45 23½	85 24
<i>d</i> 101	90 00	22 22½	67 37½	90 00	15 49	67 37½
<i>e</i> 301	90 00	45 09	44 51	90 00	38 35½	44 51
<i>D</i> 101	—90 00	10 28	100 28	90 00	17 01½	100 28
<i>E</i> 301	—90 00	37 47	127 47	90 00	44 20½	127 47
<i>p</i> 111	58 13	25 50½	67 37½	76 43½	20 32½	68 15
<i>q</i> 221	54 14½	41 07½	54 41	67 24	35 58	57 45
<i>P</i> 111	—35 27½	17 23½	100 18	75 54½	21 50	99 59
<i>Q</i> 221	—43 09½	34 58	115 34	65 17	39 42½	113 05
<i>S</i> 331	—45 21½	47 26½	127 46½	58 50	52 16	121 36½
<i>f</i> 121	38 54	33 15	67 37½	64 44½	29 31½	69 51½
<i>g</i> 131	28 16½	40 59½	67 37½	54 43	38 14½	71 53½
<i>F</i> 121	—19 36	28 26½	100 18	63 20½	31 12½	99 11½
<i>G</i> 131	—13 21½	38 11½	100 18	53 01½	40 08	98 12½
<i>H</i> 141	—10 06	46 01½	100 18	44 53	47 31	97 15
<i>i</i> 211	70 11½	36 58½	54 41	78 14½	30 52½	55 32
<i>j</i> 231	42 47½	46 12	54 41	58 01	41 57½	60 38½
<i>I</i> 211	—61 56	28 28	115 34	77 02½	34 23	65 08
<i>J</i> 231	—32 00½	42 04	115 34	52 23	45 49	69 12
<i>K</i> 241	—25 07	48 25	115 34	47 22½	51 27½	108 31
<i>r</i> 311	75 45½	46 02½	44 51	79 48	39 42½	45 45½
<i>t</i> 321	63 05	48 25½	44 51	70 12½	42 39	48 09½
<i>R</i> 311	—71 47	39 12½	127 46½	78 36	45 29	126 54½
<i>I</i> 321	—56 38½	42 51½	127 46½	68 02	48 26½	124 37
<i>V</i> 421	—64 32½	49 53½	136 59	70 48½	55 51½	133 40½

Table 2 gives the details concerning the distribution of forms on the eleven crystals measured, and shows the prominence of the various forms.

TABLE 2. COMBINATIONS ON PICKERINGITE

	1	2	3	4	5	6	7	8	9	10	11
<i>b</i> 010	x			x	x		x			x	
<i>a</i> 100					x		x				
<i>m</i> 110	x	x	x	x	x	x	x	x	x	x	x
<i>n</i> 210						x				x	
<i>w</i> 011					x		x			x	x
<i>x</i> 021					x			x			
<i>y</i> 031		x		x	x	x			x	x	
<i>z</i> 041						x					
<i>d</i> 101			x	x	x		x				
<i>e</i> 301				x			x	x	x		
<i>D</i> 101							x			x	
<i>E</i> 301						x	x		x		
<i>p</i> 111					x	x	x				x
<i>q</i> 221			x	x		x			x		x
<i>P</i> 111	x					x	x	x			
<i>Q</i> 221					x		x			x	
<i>S</i> 331							x				
<i>f</i> 121				x	x						x
<i>g</i> 131		x	x			x	x	x	x		x
<i>F</i> 121					x	x	x				
<i>G</i> 131					x	x	x			x	x
<i>H</i> 141						x				x	
<i>i</i> 211	x			x	x	x	x				
<i>j</i> 231	x	x	x	x	x			x	x		x
<i>I</i> 211					x	x					
<i>J</i> 231	x									x	x
<i>K</i> 241						x	x				x
<i>r</i> 311	x				x		x		x		x
<i>t</i> 321	x	x	x	x			x	x			
<i>R</i> 311	x				x	x					
<i>T</i> 321	x				x			x	x	x	x
<i>V</i> 421	x										

Structure cell: Space group $P 2/m$; a_0 20.8, b_0 24.2, c_0 6.17, $\beta = 95^\circ +$.
 $a_0:b_0:c_0 = 0.860:1:0.255$; contains $\text{Mg}_4\text{Al}_8(\text{SO}_4)_{16} \cdot 88\text{H}_2\text{O}$.

Habit: In long acicular tufts; as a felted mass, and as closely packed cross-fibre veinlets. Also massive.

Physical properties: Cleavage (010) poor. Fracture conchoidal. Brittle. $H = 1\frac{1}{2}$. $G = 1.73$. Luster vitreous. Color white to yellow, sometimes brown.

Optical properties: Biaxial negative,

$$2V = 60^\circ, Z \wedge c = +36^\circ, Y = b$$

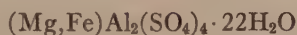
$$\alpha_{Na} = 1.475; \beta_{Na} = 1.480; \gamma_{Na} = 1.483$$

Chemistry: A hydrous magnesium aluminum sulphate $MgAl_2(SO_4)_4 \cdot 22H_2O$ corresponding to the iron compound halotrichite. The following is an analysis of the material used in this study.

PICKERINGITE (analysis by F. A. Gonyer)

Al_2O_3	12.30
MgO	4.35
CaO	0.09
H_2O+	44.66
SO_3	37.84
Insol.	0.50
Total	99.74

Relation of pickeringite to halotrichite: The two minerals form a series according to the formula



with analyses showing an apparently complete gradation between magnesium and iron. The following table shows their similarities in other respects.

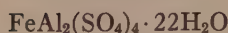
CRYSTALLOGRAPHY

	X-Ray	Ratio
Pickeringite	a_0 20.8, b_0 24.2 c_0 6.17	0.8655:1:0.2551 $\beta = 96^\circ 33\frac{1}{2}'$
Halotrichite	a_0 20.5, b_0 24.2 c_0 6.17	0.845:1:0.254 $\beta = 100.6^\circ$

OPTICS

	α	β	γ	2V	Orientation
Pickeringite	1.475	1.480	1.483	60°	$Z \wedge c = 36^\circ$ $Y = b$
Halotrichite	1.480	1.486	1.490	35°	$Z \wedge c = 38^\circ$ $Y = b$

Occurrence: Pickeringite forms snow-white tufts of fibers on massive jarosite, together with chalcantinite and fibroferite, as one of the last minerals to form at Quetena.

Halotrichite

Terminated crystals of halotrichite have never been found. However, the material of this study was in sufficiently distinct crystals for the requirements of an x-ray study with the Weissenberg goniometer. The crystallography here given, as well as the optical properties, and an analysis are new data for the species, and establish its close relationship to pickeringite, the magnesium member of the series.

Crystallography: Prism measurements on the needle-like crystals yielded forms and angles as follows:

Forms	Measured		Calculated		No. of Faces
	ϕ	ρ	ϕ	ρ	
<i>b</i> 010	0°00'	90°00'	0°00'	90°00'	19
<i>l</i> 250	24 43	90 00	24 12	90 00	4
<i>m</i> 110	49 18	90 00	48 20	90 00	38

The calculated angle is derived from the x-ray data given below.

Structure cell: Monoclinic; $a_0 = 20.47$, $b_0 = 24.24$, $c_0 = 6.167$; $\beta = 100.6^\circ \pm 1^\circ$. $a:b:c = 0.845:1:0.254$. Contains $\text{Fe}_4\text{Al}_8(\text{SO}_4)_{16} \cdot 88\text{H}_2\text{O}$.

Habit: Prismatic [001]; common forms *b m*; vertical zone striated [001]; crystals commonly acicular in radiating or matted aggregates, larger crystals commonly hollow [001].

Cleavage: (010) poor.

Physical properties: Fracture conchoidal, brittle. $G = 1.895$. $H = 1\frac{1}{2}$. Luster, vitreous; silky in fibrous aggregates. Colorless to light green.

Optical properties:

$n(\text{Na})$	
$\alpha = 1.480$	Negative
$\beta = 1.486$	$2V = 35^\circ$
$\gamma = 1.490$	$r > v$, medium
	$Z/\wedge c = 38^\circ$ $Y = b$

Composition: An analysis on material used for the optical and x-ray study was made by F. A. Gonyer, as follows:

Al_2O_3	10.26
Fe_2O_3	0.65
FeO	7.28
$\text{H}_2\text{O}+$	43.33
SO_3	37.28
CuO	0.66
Insol.	0.93
Total	100.39

This is in good agreement with the formula.

Pyrognostics: Closed tube yields abundant acid water; B.B. decrepitate. Readily soluble in water and acids.

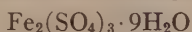
Occurrence: Occurs at all three deposits intimately associated with pyrite, szomolnokite and other iron sulphates.

Halotrichite is an early mineral, apparently forming directly from pyrite by action of solutions carrying aluminum sulphate. Occurs as an alteration product of szomolnokite. Apparently the presence or absence of aluminum sulphate determines whether szomolnokite or halotrichite forms. It occurs at Chuquicamata in crystals up to one-sixteenth of an inch thick in a groundmass of pyrite, sericite and aluminum sulphate.

C. Klauer¹ found that halotrichite only formed in iron aluminum sulphate solutions that contained an excess of sulphuric acid and, when the excess acid failed, precipitation ceased. The natural associations point to an excess of sulphuric acid at the time of formation of this mineral.

REFERENCE. ¹ Klauer, *Ann. f. Pharm.*, vol. 14, p. 261, 1835.

Coquimbite and Paracoquimbite



Coquimbite was first described from Chile,¹ where it is more abundant than in other described occurrences. Recently an exhaustive crystallographic study was made by Ungemach² on material from the type locality, with the conclusion that the mineral represents dimorphous forms, for one of which, the hexagonal form, the name coquimbite is retained, and the other, the rhombohedral modification, is called para-coquimbite. These two forms have been verified by the writer.

Analyses of the material of this study, are as follows:

	1	2	3
Fe ₂ O ₃	27.5	28.71	28.5
CuO	2.8		
CaO	1.5		
SO ₃	39.9	42.31	42.8
H ₂ O	28.4	28.82	28.7
Insol.		0.40	
Total	100.1	100.24	100.0

1. Chuquicamata. Bert Carter, Chile Exploration Co., analyst. Includes SiO₂, Al₂O₃, MgO trace.

2. Alcaparrosa. Deep amethystine color. E. P. Henderson, U. S. National Museum, analyst.

3. Theoretical for Fe₂(SO₄)₃ · 9H₂O.

Coquimbite is not a common mineral at Chuquicamata. It has been observed in several specimens, but it apparently disappears rapidly in depth.

Both coquimbite and paracoquimbite occur at Quetena, coquimbite being the more common in the specimens studied. It is commonly associated with voltaite, a later mineral. It is less commonly associated with szomolnokite, roemerite and quenstedtite. Both szomolnokite and roemerite are earlier minerals and the relationships with quenstedtite are not clear. The latter mineral appears to be the later. The coquimbite is always light in color.

Both coquimbite and paracoquimbite are abundant at Alcaparrosa, the rhombohedral modification, paracoquimbite, greatly predominating. The mineral ranges in color from a pale violet to a deep amethystine. Crystals up to three-quarters of an inch in size are present.

The sequence relationships of the mineral are given below,

<i>Late</i>	Lapparentite
	Quenstedtite
	Coquimbite
	Roemerite
<i>Early</i>	Szomolnokite

An attempt was made to determine which modification was the earlier, the hexagonal or the rhombohedral. The data is conflicting but it is believed by the writer that the hexagonal coquimbite is the earlier form.

REFERENCES. ¹ Rose, *Pogg. Ann.*, vol. 27, p. 310, 1833.

² Ungemach, *Bull. Soc. Min.*, vol. 58, p. 165, 1935.

Kroehnkite



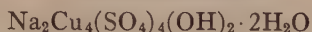
Kroehnkite is a common mineral in northern and central Chile and a rare mineral elsewhere in the world. In portions of the deposit at Chuquicamata it constitutes an ore mineral. Crystals are common, and it also forms cross-fibre veins. The largest crystal found measures one-half by one-quarter by three and one-quarter inches. The crystallography of kroehnkite in its present form was first established¹ after a study of crystals from Chuquicamata. In this study the following forms were observed: *a b m h e d q s w x*.

In the oxidation of chalcocite in the northern portion of the ore deposit at Chuquicamata, chalcantite is usually the first sulphate to form. This is followed by kroehnkite, and antlerite replaces the kroehnkite. Along the western side of the ore body, kroehnkite is characteristically associated with atacamite and natrochalcite. The deposition of pure kroehnkite was followed by the simultaneous deposition of kroehnkite and acicular atacamite. Toward the end of this period of deposition, atacamite began to crystallize in pyramidal crystals and continued to

form beyond the period of the kroehnkite. Natrochalcite forms crusts over these minerals and is definitely later. In the southern part of the deposit early bloedite is commonly replaced by kroehnkite.

REFERENCE. ¹ Palache and Warren, *Am. Jour. Sci.*, vol. **24**, p. 342, 1904; *Zeits. Krist.*, vol. **45**, p. 529, 1908.

Natrochalcite



Natrochalcite is a rare mineral found only at Chuquicamata, in beautiful bright emerald-green crystals. The mineral was described in 1908.¹ It was limited to the upper portions of the deposit and in recent years has become increasingly rare. The mineral occurs coating cracks in the altered country rock or as crystalline crusts on kroehnkite and atacamite. Rarely it occurs in vugs in fibrous kroehnkite.

The paragenesis was incompletely determined in this study. A definite sequence was,

<i>Late</i>	Natrochalcite
	Atacamite
<i>Early</i>	Kroehnkite

No minerals were found coating the natrochalcite and nothing can be said regarding minerals that are later.

REFERENCE. ¹ Palache and Warren, *Am. Jour. Sci.*, vol. **24**, p. 342, 1908; *Zeits. Krist.*, vol. **45**, p. 529, 1908. The formula given above is a correction of that in the original paper.

Ferrinatriite



The mineral ferrinatriite was first described by Mackintosh.¹ Later the composition was verified by Genth² and Frenzel.³ Recently a mineral was found in Chile and named leucoglaucite by Ungemach,⁴ on the basis of a chemical analysis of a very small sample. In all other respects the mineral matches ferrinatriite closely. The mineral collected by the writer is similar in its physical properties to these two previously described minerals but differs from both chemically. The formulae derived from the analyses are:

(1) Ferrinatriite	$\text{Na}_3\text{Fe}(\text{SO}_4)_3 \cdot 3\text{H}_2\text{O}$
(2) Leucoglaucite	$\text{H Fe}(\text{SO}_4)_2 \cdot 2\text{H}_2\text{O}$
(3) Ferrinatriite-Bandy	$\text{Na}_4\text{Fe}_2(\text{SO}_4)_5 \cdot 7\text{H}_2\text{O}$

Since four analyses in good agreement have been made of ferrinatriite, the first of these formulae is the best established, on chemical grounds. Further, the three minerals are admittedly hexagonal, so that from structural considerations the first is also most likely since two molecular

weights of the first formula would give the proper number of atoms and molecular groups to distribute in hexagonal space groups. On the basis of symmetry the last formula is least suitable.

The following table lists chemical analyses and physical properties of the three minerals under consideration.

	Ferrinatrite				Ferrinatrite Bandy	Leucoglaucite
	1	2	3	4	5	6
Na ₂ O	18.34	19.95	20.22	20.06	19.92	
K ₂ O	0.40	tr.			0.40	
CaO		0.22				
Fe ₂ O ₃	17.23	17.30	17.69	16.91	19.00	28.06
Al ₂ O ₃	0.43					
SO ₃	50.25	51.30	50.85	51.29	49.75	56.97
H ₂ O	11.14	11.89	11.90	11.50	15.13	15.02
Insol.	2.00				0.30	
Total	99.79	100.66	100.66	99.76	100.54	100.05
G		{2.547 2.578	2.61		2.57	2.52*
ω		1.558			1.557	1.559*
ϵ		1.613			1.615	1.627*
$a:c$			0.55278		0.5582	0.5589

* Determined on type material kindly sent by Professor Ungemach.

1. Ferrinatrite. Mackintosh, analyst.¹

2. Ferrinatrite. Genth, analyst.²

3. Ferrinatrite. Frenzel, analyst.³

4. Ferrinatrite. Scharizer, analyst.⁵

5. Ferrinatrite-Bandy. E. P. Henderson, analyst. Unpublished.

6. Leucoglaucite. Ungemach, analyst.⁴

Physical properties: The Chuquicamata ferrinatrite has G 2.57, H 2½. Fracture splintery; fibers brittle. Cleavage {1010} perfect. Color pale amethystine.

Habit: Prismatic to fibrous [0001], deeply striated. Often in parallel growths. Common forms: $b(11\bar{2}0)$, $p(10\bar{1}1)$.

Occurrence: As fibrous crusts associated with metasideronatrite and metavoltine at Chuquicamata. The former shows some evidence of replacing ferrinatrite and pseudomorphs have been observed. Metasideronatrite may be changed to ferrinatrite by treating with a solution containing an excess of sodium sulphate and sulphuric acid. This may account for the overlapping of the sequence of these two minerals since they seem to alter, one to the other, with ease, in both directions.

REFERENCES. ¹ Mackintosh, *Am. Jour. Sci.*, vol. **38**, p. 243, 1889.

² Gentz, *Zeits. Krist.*, vol. **18**, p. 586, 1891.

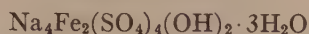
³ Frenzel, *Zeits. Krist.*, vol. **18**, p. 596, 1891.

⁴ Ungemach, *Bull. Soc. Min.*, vol. **58**, p. 97, 1935.

⁵ Scharizer, *Zeits. Krist.*, vol. **41**, p. 412, 1906.

Scharizer, in Doelter, **4**[1], 582, 1929.

Metasideronatrite



This mineral is newly described here. It differs from sideronatrite only in having less water, and consequently higher refractive indices and higher density. The relation between the two is shown below:

Formula	METASIDERONATRITE	SIDERONATRITE
	$\text{Na}_4\text{Fe}_2(\text{SO}_4)_4(\text{OH})_2 \cdot 3\text{H}_2\text{O}$	$\text{Na}_4\text{Fe}_2(\text{SO}_4)_4 \cdot (\text{OH})_2 \cdot 6\text{H}_2\text{O}$
G	2.46	2.2-2.3
α	1.543	1.508
β	1.575	1.525
γ	1.634	1.586
2V	60°	58°

Metasideronatrite can be produced from sideronatrite by dehydration over sulphuric acid. Whether the Chuquicamata material has gone through a dehydration is not certain, but no evidence of alteration is visible in the specimens, which are fresh, the cleavage flakes being quite transparent.

The minerals *urusite*¹ and *bartholomite*² are apparently related to the minerals here discussed, but the data are so meager that a decision concerning their nature cannot be reached.

Since this species is named here for the first time a complete description is given.

Crystallography: Orthorhombic; dipyrarnidal— $2/m \ 2/m \ 2/m$

$$a:b:c=0.4571:1:0.1187$$

$$p_0:r_0:r_0=0.2579:0.1187:1$$

$$q_1:r_1:p_1=0.4571:3.8598:1$$

$$r_2:p_2:q_2=8.4246:2.1877:1$$

Forms	ϕ	$\rho=C$	ϕ_1	$\rho_1=A$	ϕ_2	$\rho_2=B$
<i>b</i> 010	0°00'	90°00'	90°00'	90°00'	—	0°00'
<i>m</i> 110	65 26	90 00	90 00	24 34	0°00'	65 26
<i>e</i> 011	0 00	6 46	6 46	90 00	90 00	83 14

Forms	No. of faces	ϕ	Measured
<i>b</i> 010	10	0°00'	90°00'
<i>m</i> 110	21	62°48'–67°59'	90 00
<i>e</i> 011	2	89 49–89 58	6°44'–6°48'

Habit: Prismatic [001] crystals rare; usually in coarse to fine crystalline aggregates.

Cleavage: {100} {010} perfect, {001} eminent.

Physical properties: Fracture, fibrous; $G=2.46$; $H=2.5$. Luster, silky. Color golden yellow to straw yellow.

Optical properties:

$\alpha=a$ =colorless	=1.543	Positive
$\beta=b$ =light yellow	=1.575	$2V=60^\circ$
$\gamma=c$ =brownish yellow	=1.634	$r>v$, strong

Chemistry: Basic hydrous sodium-iron sulphate, $\text{Na}_4\text{Fe}_2(\text{SO}_4)_4(\text{OH})_2 \cdot 3\text{H}_2\text{O}$.

ANALYSIS BY E. P. HENDERSON

		Mol. Ratios	
Fe_2O_3	22.90	.1434	1.00
Na_2O	17.56	.2832	1.99
K_2O	.26	.0028	
SO_3	48.66	.6077	4.23
H_2O	9.75	.5411	3.77
Insol.	.60		
Total	99.73		

Insoluble in cold water. Soluble in boiling water with decomposition; soluble in dilute acids.

Pyrognostics: B.B. gives strong soda flame, colors bead dark brown. Closed tube yields abundant acid water. Insoluble in cold water.

Occurrence: At Chuquicamata intimately associated with metavoltine, less commonly with ferrinatrite, ungemachite, alums and natrojarosite.

REFERENCES. ¹ Frenzel, *Min. Mitt.*, vol. 2, p. 133, 1879.

² Cleve, *Ak. Stockholm*, vol. 9, Nov. 1870.

Roemerite



The crystallography of roemerite has been variously interpreted. The final satisfactory setting of this triclinic mineral is that of Wolfe.¹ No crystals were encountered in this study, but roemerite is an abundant mineral at Alcaparrosa where it is associated with szomolnokite and rhomboclase during an early phase of pyrite oxidation. The following optical properties were determined on fresh material: $\alpha=1.526$, $\beta=1.564$, $\gamma=1.575$; $2V=50^\circ$; $r>v$ =extreme.

No analysis of material was made as the mineral commonly showed incipient alteration to coquimbite. The color was most intense and the mineral was purest in narrow halos about areas of pyrite and szomolnokite. In the change from roemerite to coquimbite the amounts of iron and oxygen remain the same, sulphur is added and water decreases in amount. At Quetena and Chuquicamata roemerite is a relatively rare mineral compared to coquimbite with which it is closely associated.

REFERENCE. ¹ Wolfe, *Am. Mineral.*, vol. 22, p. 736, 1937.

Metavoltine?

The writer has not been able to definitely identify the mineral here described. It approaches most closely the originally described metavoltine,¹ with, however, important differences. The mineral referred to metavoltine by Zambonini² is probably not really that species, nor is it related to the mineral here described. The artificial products of Scharizer³ and Gossner⁴ are undoubtedly of the same composition as Zambonini's mineral, but they are not metavoltine.

The crystallography of the material from Chuquicamata is contained in the following table:

Hexagonal; dipyramidal—6/ <i>m</i> <i>c</i> = 2.5143 <i>ρ</i> ₀ = 1.4517					
Forms	No. of Faces	Measured		Calculated	
		<i>φ</i>	<i>ρ</i>	<i>φ</i>	<i>ρ</i>
<i>c</i> 0001	12	—	0°00'	—	0°00'
<i>a</i> 10 $\bar{1}$ 0	3	0°00'	90 00	0°00'	90 00
<i>b</i> 11 $\bar{2}$ 0	1	30 00	90 00	30 00	90 00
<i>p</i> 10 $\bar{1}$ 1	1	0 00	55 26	0 00	55 26
<i>l</i> 20 $\bar{2}$ 1	1	0 00	71 00	0 00	71 00
<i>c</i> 40 $\bar{4}$ 1	1	0 00	78 40	0 00	80 14
<i>e</i> 60 $\bar{6}$ 1	1	0 00	83 15	0 00	83 27

Habit: In aggregates of six-sided plates and scales; common forms: *o a*; crystals very rare; parallel growth [0001] common.

Cleavage: {0001} perfect

Physical properties: Fracture, rough and interrupted, plates slightly flexible; *G* = 2.5, 2.53, 2.396. *H* = 2½. *F* = 5. Luster vitreous to oily.

Optical properties: Color olive green to greenish brown.

<i>n</i>		
<i>ω</i> (brown)	1.589-1.590	Negative
<i>ε</i> (pale greenish yellow)	1.572-1.574	

Chemistry: In order to show the relation of the Chuquicamata mineral to metavoltine, as described, and to Zambonini's mineral, as well as the artificial material, a table of chemical analyses is given below:

	ANALYSES OF METAVOLTINE AND RELATED MINERALS				
	1	2	3	4	5
Fe ₂ O ₃	21.20	21.03	23.31	22.03	21.54
FeO	2.92				
K ₂ O	9.87	21.49	4.69	21.22	21.44
Na ₂ O	4.65		8.15		
SO ₃	46.90	42.98	45.42	43.84	42.86
H ₂ O	14.58	14.35	17.83	21.91	14.49
Total	100.12	99.85	99.56	100.00	100.33
G	2.53		2.5	2.396	

1. Metavoltine. Blaas, analyst.¹ Persia.
2. Metavoltine? Zambonini, analyst.² Vesuvius.
3. Metavoltine? Henderson, analyst (Unpublished). Chuquicamata.
4. Artificial. Scharizer, analyst.³
5. Artificial. Gossner.⁴

The analyses given above indicate the following formulae:

(1) Metavoltine, Blaas	$K_4Na_3(Fe''Fe''')(SO_4)_{12} \cdot 16H_2O$
(2) Metavoltine? Zambonini	$K_{10}Fe_6'''(SO_4)_{12}(OH)_4 \cdot 16H_2O$
(3) Metavoltine? Henderson	$K_2Na_6Fe_6'''(SO_4)_{12}(OH)_2 \cdot 20H_2O$

Since the data at hand are not definite, no statement can be made concerning the validity of the formulae listed. Zambonini's material is most probably correctly formulated, since several analyses of similar artificial material are available.

General experience in sodium and potassium salts indicates that little isomorphism exists between them. Mixed crystals are usually not formed, so that the three substances here discussed may well be different minerals.

Pyrognostics: Partially soluble in water and dilute acids. On heating, the aqueous solution yields reddish precipitate. In closed tube yields water and forms black residue.

Occurrence: At Alcaparrosa metavoltine (?) occurs surrounded by a halo of copiapite in veins of pickeringite. The age relationships are metavoltine followed by copiapite with the pickeringite the younger mineral.

At Quetena metavoltine (?) is intimately associated with metasideronatrite, but the mineral is so uncommon that the age relationship was uncertain. Jarosite is later than the two minerals.

Metavoltine (?) is almost always associated, more or less intimately with metasideronatrite at Chuquicamata. The latter may occur without metavoltine, but in the writer's experience metavoltine (?) never occurs without associated metasideronatrite. With one exception, every occurrence appears to show the metavoltine (?) as the younger mineral. In a single specimen the metasideronatrite is certainly the younger mineral. Commonly associated with the two minerals are a number of members of the alum group such as kalinite, pickeringite, tamarugite. All of these minerals are normal sulphates and later than metavoltine (?) and metasideronatrite. Other associated minerals that are later are ungemachite and jarosite.

REFERENCES. ¹ Blaas, *Ak. Wien. Ber.*, vol. 87, p. 155, 1883.

² Zambonini, *Atti R. Acc. Napoli*, 8, 13, 1906.

³ Scharizer, *Zeits. Krist.*, vol. 58, p. 424, 1923.

⁴ Gossner and Arm, *Zeits. Krist.*, vol. 72, p. 205, 1929.

Copiapite and Cuprocopiapite

Copiapite is common in all three of the deposits studied here, and often as very fine small crystals. These crystals were studied by Professor Palache, who found the mineral to be triclinic, not orthorhombic or monoclinic as it had been previously regarded. The same conclusion regarding the symmetry of this mineral was simultaneously arrived at by Ungemach.¹

ANALYSES OF COPIAPITE

No.	β	Fe ₂ O ₃	SO ₂	H ₂ O	Na ₂ O— K ₂ O	MgO	FeO	CuO	Al ₂ O ₃	Insol.
1.	1.550	28.95	39.56	28.60		Tr.	.52		1.31	1.06
2.	1.546	30.75	39.28	29.97						
3.	1.545	29.98	39.68	30.45						.31
4.	1.543	23.21	38.44	27.76	.16		4.01	1.0	3.62	.52
5.	1.541	25.04	38.36	29.71		.29	.44		.31	5.43
6.	1.540	24.93	39.10	29.92	.40		.78		3.49	1.24
7.	1.538	24.96	37.92	31.51		3.10			.52	1.96
8.	1.535	27.44	39.47	27.84		3.26	.52			1.16
9.	1.532	26.10	38.37	30.68			4.06		Tr.	.71
10.	1.531	21.91	38.87	33.33			.94		4.15	.61
11.	1.530	26.25	39.24	28.32		3.47	1.04		.08	.48
12.	1.53	26.39	39.79	29.92		3.19				.30
13.	1.529	29.66	39.81	29.95			.33			.30
14.		27.28	39.83	29.92						.55
15.	1.591	27.66	41.62	23.51				5.72	1.47	.21
16.		26.8	33.5	29.0	.40	0.2		6.6		2.7

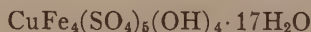
1. Atacama Desert, Chile. W. F. Foshag, analyst; unpublished.
 2. Artificial. Posnjak and Merwin, *Jour. Am. Chem. Soc.*, vol. **44**, p. 1980, 1922.
 3. Congo Mine, Perry Co., Ohio. Caughey, *Am. Mineral.*, vol. **3**, p. 162, 1918.
 4. Island Mountain, Calif. W. F. Foshag, analyst; unpublished.
 5. Leona Heights, Calif. W. F. Foshag, analyst; unpublished.
 6. Temple Rock, Utah. W. F. Foshag, analyst; unpublished.
 7. Laird Post, B. C. Todd, analyst; Walker, *Univ. Toronto Studies, Geol. Ser.*, vol. **14**, p. 84, 1922.
 8. Blythe, Calif. W. F. Foshag, analyst; unpublished.
 9. Capo d'Arco, Elba. Manasse, *Proc. verb. Soc. Toscana*, **1911**.
 10. Vignera, Elba. Manasse, **1911**.
 11. Las Vegas, N. Mex. W. F. Foshag, analyst; unpublished.
 12. Santa Maria Mts., Calif. Schairer and Lawson, *Am. Mineral.*, vol. **9**, p. 242, 1924.
 13. Copiapo, Chile. Manasse, **1911**.
 14. Chuquicamata, Chile. F. A. Gonyer, analyst; unpublished.
 15. Chuquicamata, Chile. Cuprocopiapite. F. A. Gonyer, analyst; unpublished.
 16. Chuquicamata, Chile. B. W. Carter, analyst; unpublished.
- On analyses 1, 4, 5, 6, 8, 11—refractive indices by Larsen, *Bull. 679, U. S. Geol. Surv.*, 1921.

An attempt to correlate the refractive index (β) with the variations in composition of copiapites from Chile, and elsewhere, led to no conclusive results. In the following table is a list of analyses of copiapites, together with measurements of the β index. The writer is indebted to Dr. W. F. Foshag for the privilege of publishing here the six analyses credited to him.

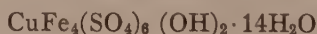
Synthetic copiapite² yields a formula $\text{Fe}_4(\text{SO}_4)_5(\text{OH})_2 \cdot 16\text{H}_2\text{O}$. Analyses of natural copiapites vary considerably and the water content is frequently $18\text{H}_2\text{O}$. Analyses 7, 8, 11 and 12 are in good agreement with the formula



The cuprocopiapite composition (anal. 16) is most closely represented by the formula



or, using analysis 15, the formula may be written



Occurrence: Copiapite is an abundant mineral in all three deposits. It is relatively most abundant at Alcaparrosa, where it occurs in thick layers of clear, brilliant crystalline aggregates. It may be used as a "key mineral" in the sequence study, as it is one of the earliest basic minerals, with the possible exception of fibroferite.

Cuprocopiapite is always associated with copiapite, commonly with parabutlerite, chalcantite and jarosite. It is later than the first-men-

tioned two minerals and earlier than the last two. It is probably formed by the reaction between copiapite and sulphate solutions carrying copper. At Quetena it occurs in rounded masses, within massive iron sulphates, usually copiapite.

REFERENCES. ¹ Ungemach, *Bull. Soc. Min.*, vol. 58, p. 97, 1935.

² Posnjak and Merwin, *Jour. Am. Chem. Soc.*, vol. 44, p. 1965, 1922.

³ From unpublished results of M. Fleisher (1935) and M. A. Peacock (1938).

Quenstedtite

$\text{Fe}_2(\text{SO}_4)_3 \cdot 10\text{H}_2\text{O}$ Triclinic, pinacoidal

The crystal form of quenstedtite was first correctly established by Ungemach,¹ whose data we use. One new form on quenstedtite was observed in this study,

		Calculated		Measured	
		ϕ	ρ	ϕ	ρ
<i>n</i>	032	$21^\circ 44\frac{1}{2}'$	$29^\circ 17\frac{1}{2}'$	$21^\circ 20'$	$29^\circ 58'$

The mineral occurs in tabular crystals {010}. The color does not agree with that given by Linck² and Ungemach.¹ The material from Alcaparrosa is colorless to pale violet, differing from the "rose-lilas intense" color of the Copiapo material.

The optical properties of the Alcaparrosa material are tabulated below (as obtained in a measured crystal oriented on the Fedorov stage).

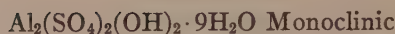
	ϕ	ρ	$n(\text{Na})$	
α	— 43°	45°	1.547	Positive
β	128°	43°	1.566	$2V=70^\circ$
γ	-138°	88°	1.594	$r < v$ strong; horizontal

Extinction on (010) against [001] = 30° .

Quenstedtite was only observed from Alcaparrosa. There it occurs intimately associated with coquimbite and lapparantite. In association with coquimbite it shows a remarkable case of replacement by alteration. Most of the quenstedtite is altered to coquimbite. Apparently the latter mineral forms earlier than quenstedtite but, due to the strong overlapping of their stability fields, both can form at essentially the same time. Within the range of the overlapping fields the quenstedtite alters readily to coquimbite through the loss of one molecule of water. Unaltered material occurs as crystal druses in the coquimbite and in rounded aggregates of minute crystals in copiapite.

REFERENCES. ¹ Ungemach, *Bull. Soc. Franc. Min.*, vol. 58, p. 97, 1935.

² Linck, *Zeits. Krist.*, vol. 15, p. 11, 1889.

Lapparentite

Lapparentite is a new mineral recently described by Ungemach¹ from Tierra Amarilla, Chile. This mineral was found at Alcaparrosa, near Cerritos Bayos, thus adding a new locality. It occurs in colorless tabular crystals, rather difficult to tell from quenstedtite with which it is commonly associated. All of the forms observed by Ungemach were found in this study with the exception of the base, and eight additional new forms were observed. It is to be noted that Ungemach found no orthodomies, and only the positive and negative unit orthodomies were observed in this study. The new forms are given below.

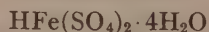
Forms	No. of Faces	Measured		Calculated from Ungemach's Ratio	
		ϕ	ρ	ϕ	ρ
140	4	39°53'	90°00'	40°41'	90°00'
150	3	34 07	90 00	34 31	90 00
160	4	30 05	90 00	29 49	90 00
180	2	23 32	90 00	23 16	90 00
1.12.0	2	16 15	90 00	16 00	90 00
101	2	89 42	42 34	90 00	42 27½
101	1	—89 17	36 24	—90 00	36 44
141(?)	1	—37 32	50 51	—37 41	50 40½

Optical properties: The optical properties for this species have not yet been recorded. Doctor Ungemach kindly furnished crystals of the original material, and the optical properties were determined on this as well as on crystals from the newer occurrence here given.

Biaxial positive.	2V = 55° +
$\alpha = 1.490$	Y = b
$\beta = 1.492$	X \wedge c = +5°
$\gamma = 1.504$	

At Alcaparrosa, lapparentite occurs in tabular crystals associated with quenstedtite in vugs in coquimbite and with pickeringite. Quenstedtite and coquimbite are earlier minerals, and pickeringite is later. However, some pickeringite appears to be earlier.

REFERENCE. ¹ Ungemach, *Bull. Soc. Franc. Min.*, vol. 58, p. 209, 1935.

Rhombochase

This new species, recently described from Szomolnok, Czecho-

slovakia,¹ has been found by the writer at Alcaparrosa. This marks the second occurrence. Since the material available for this study was in good crystals, a complete redescription is here given. The crystallography has been amplified by a more complete form list and a more accurate axial ratio. The refractive indices have been determined. Several other physical properties have been measured.

Crystallography:

Orthorhombic; dipyramidal

$$a:b:c=0.5577:1:0.9370$$

$$p_0:q_0:r_0=1.6801:0.9370:1$$

$$q_1:r_1:p_1=0.5577:0.5952:1$$

$$r_2:p_2:q_2=1.0672:1.7930:1$$

Forms	Calculated		No. of Measurements	Measured		Krenner's Measurements		Krenner's Forms
	ϕ	ρ		ϕ	ρ	ϕ	ρ	
<i>c</i> 001	—	0°00'	11	—	0°00'			x
<i>b</i> 010	0°00'	90 00'	10	0°00'	90 00'			x
<i>s</i> 120	41 53	90 00	3	41 42	90 00			x
<i>m</i> 110	60 51	90 00	19	60 51	90 00	58°36'	90 00'	x
<i>t</i> 041	0 00	75 02	2	00 00	75 13			
<i>n</i> 118	60 51	13 31	3	60 56	13 01			
<i>r</i> 114	60 51	25 41	1	58 10	25 00			
<i>v</i> 113	60 51	32 40	3	58 00	31 00			
<i>w</i> 223	60 51	52 03	6	60 45	52 10			
<i>p</i> 111	60 51	62 32	10	60 51	62 32	62 38		x
<i>q</i> 221	60 51	75 26	5	58 00	75 28			
<i>u</i> 241	41 53	78 46	2	41 44	78 40			

Krenner's axial ratio is

$$a:b:c=0.5695:1:0.94644.$$

All the forms observed by Krenner were also found by the writer. Additional forms are given in the table.

Habit: Tabular {001}; base shows etch forms, common forms: *b c m p*.

Cleavage: {001}, perfect, {110}, excellent.

Physical properties: Fracture conchoidal to fibrous, cleavage folia are flexible and polished. $G=2.23$. $H=2$. Luster pearly to subvitreous. Colorless to gray.

Optical Properties:

	$n(\text{Na})$	
$\alpha=[001]$	1.534	Negative $2V=27^\circ$
$\beta=[100]$	1.553	
$\gamma=[010]$	1.638	

Pyrognostics: Slowly soluble in water. Insoluble in NH_4OH but forms a brown coating over mineral (iron hydroxide?). Soluble in acids. B.B. decrepitates and fuses to a dark brown bead.

Occurrence: Rhomboclase occurs at Alcaparrosa, near Cerritos Bayos, intimately associated with szomolnokite and roemerite. It is believed to be later than either of these minerals. The formation of this mineral and a detailed description of the mineral relationships has been given in the section on geochemistry.

REFERENCE. ¹ Krenner, *Centralbl. Min.*, A, p. 265, 1928.

Parabutlerite



A basic hydrate of iron of this same composition has already been described as the mineral butlerite¹ and as an artificial compound² in the system $\text{Fe}_2\text{O}_3\text{-SO}_3\text{-H}_2\text{O}$. However, the mineral here called parabutlerite is orthorhombic, prismatic in habit; the artificial substance is presumably monoclinic;² the originally described butlerite has been erroneously assigned to the orthorhombic system but is really triclinic.

Parabutlerite, both by its crystallography and optical properties as given later, is definitely orthorhombic. Butlerite has been re-examined during this study, and the conclusion was reached that it is triclinic because microscopic examination shows a twin plane in the position (100) of Lausen's¹ orientation. The optical orientation within each individual is such that the most probable symmetry is triclinic.

The artificial compound is in diamond-shaped crystals with possible twinning on (30 $\bar{1}$) and (20 $\bar{3}$). This suggests the possibility that the artificial material may be the same as butlerite. Actual crystallographic measurements of the artificial substance were not included in the work cited, but the ratio and forms were given.

The following table compares the modifications here discussed.

TABLE OF COMPARISON

Symmetry	Parabutlerite Orthorhombic	Butlerite Triclinic (pseudo- orthorhombic)	Artificial Monoclinic
Ratio	$a:b:c=$ 0.7310:1:0.7218	0.9005:1:1.3606	0.858:1:1.358 $\beta=71^\circ 24'$
α	1.598	1.604	1.588
β	1.663	1.674	1.678
γ	1.737	1.731	1.749
G	2.55	2.548	
H	$2\frac{1}{2}$	$2\frac{1}{2}$	

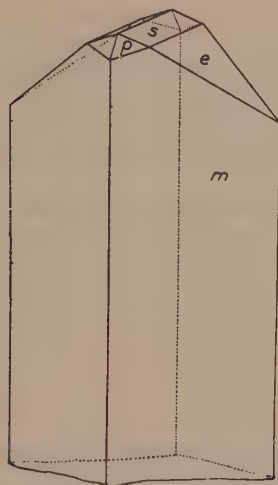


FIG. 6. Crystal of Parabutlerite.

The following full description of parabutlerite is given here since the mineral is first named and described in this study.

Crystallography: Orthorhombic; bipyramidal— $2/m\ 2/m\ 2/m$

$$a:b:c=0.7310:1:0.7218$$

$$p_0:q_0:r_0=0.9874:0.7218:1$$

$$q_1:r_1:p_1=0.7310:1.0128:1$$

$$r_2:p_2:q_2=1.3855:1.3680:1$$

Forms	ϕ	$\rho=C$	ϕ_1	$\rho_1=A$	ϕ_2	$\rho_2=B$
<i>l</i> 140	$19^\circ 30\frac{1}{2}'$	$90^\circ 00'$	$90^\circ 00'$	$70^\circ 29\frac{1}{2}'$	$0^\circ 00'$	$19^\circ 30\frac{1}{2}'$
<i>m</i> 110	53 50	90 00	90 00	36 10	0 00	53 50
<i>s</i> 012	0 00	$19\ 50\frac{1}{2}$	$19\ 50\frac{1}{2}$	90 00	90 00	$70\ 09\frac{1}{2}$
<i>f</i> 034	0 00	$28\ 25\frac{1}{2}$	$28\ 25\frac{1}{2}$	90 00	90 00	$61\ 34\frac{1}{2}$
<i>e</i> 011	0 00	35 49	35 49	90 00	90 00	54 11
<i>g</i> 032	0 00	$47\ 16\frac{1}{2}$	$47\ 16\frac{1}{2}$	90 00	90 00	$42\ 43\frac{1}{2}$
<i>d</i> 101	90 00	44 38	0 00	45 22	45 22	90 00
<i>p</i> 111	53 50	50 44	$35\ 49\frac{1}{2}$	51 19	45 22	62 49
<i>r</i> 212	$69\ 55\frac{1}{2}$	46 26	$19\ 50\frac{1}{2}$	47 07	45 22	75 36

Habit: Prismatic [001] (Fig. 6) common forms: *m s e p*; prism zone striated [001].

Cleavage: {110} poor.

Physical Properties: Fracture conchoidal, brittle. $G=2.55$. $H=2.5$.

Luster, vitreous.

Optical Properties: Color light orange to light orange-brown.

	$n(\text{Na})$	
$\alpha = b =$ pale yellow	1.598	Positive
$\beta = c =$ greenish yellow	1.663	$2V = 87^\circ$
$\gamma = a =$ brownish yellow	1.737	$r > v$, moderate

Composition: Basic hydrous iron sulphate, $\text{Fe}(\text{SO}_4)(\text{OH}) \cdot 2\text{H}_2\text{O}$.

ANALYSIS (Henderson, U. S. National Museum) ^a			
	Per cent	Molecular Ratios	
Fe_2O_3	39.21	.2455	1.00
SO_3	39.15	.4889	1.99
H_2O	22.00	1.2210	4.97
Insol.	.23		
Total	100.59		

Pyrognostics: B.B. dark brown; closed tube, yields acid water; insoluble in water, hot or cold, ammonia, soluble in dilute acids.

Occurrence: Occurs at Alcaparrosa near Cerritos Bayos in a bed about 8 inches thick above copiapite. It results from the alteration of copiapite and in part is pseudomorphous after copiapite. It also occurs with copiapite and jarosite at Quetena and Chuquicamata.

All of the field evidence points to the conclusion that parabutlerite formed after copiapite. This evidence is conformable with the findings of Posnjak and Merwin² in their study of the system $\text{Fe}_2\text{O}_3\text{-SO}_3\text{-H}_2\text{O}$. At 50 degrees they found that these minerals formed from the following solutions.

COMPOSITION OF SOLUTION

	weight per cent			
	$\text{SO}_3/\text{Fe}_2\text{O}_3$	Fe_2O_3	SO_3	H_2O
$\text{Fe}(\text{SO}_4)\text{OH} \cdot 2\text{H}_2\text{O}$	2.55-2.69	17.96-20.13	22.96-27.18	59.08-52.69
Copiapite	2.74-3.66	20.70-16.78	28.40-30.72	50.90-52.50

Jarosite is later than parabutlerite. The definitely established sequence is:

Jarosite
Parabutlerite
Copiapite
Coquimbite

Much of the parabutlerite at Quetena and Chuquicamata is associated with copiapite and jarosite and shows the same sequence relationships as at Alcaparrosa. One specimen showed the parabutlerite as having formed during the formation period of copiapite at Quetena. Posnjak and Merwin obtained both the compound $\text{Fe}_2\text{O}_3 \cdot 2\text{SO}_3 \cdot 5\text{H}_2\text{O}$

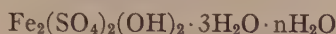
and copiapite from a solution of the composition Fe_2O_3 , 21.0; SO_3 , 28.2; H_2O , 50.8.

REFERENCES. ¹ Lausen, *Am. Mineral.*, vol. **13**, p. 203, 1928.

² Posnjak and Merwin, *Jour. Am. Chem. Soc.*, vol. **44**, p. 1965, 1922.

³ Henderson, U. S. National Museum, unpublished data on the material of this study.

AMARANTITE GROUP



Hohmannite	$\text{Fe}_2(\text{SO}_4)_2(\text{OH})_2 \cdot 3\text{H}_2\text{O} \cdot 4\text{H}_2\text{O}$
Castanite	
Amarantite	$\text{Fe}_2(\text{SO}_4)_2(\text{OH})_2 \cdot 3\text{H}_2\text{O} \cdot 3\text{H}_2\text{O}$
Paposite	
Metahohmannite	$\text{Fe}_2(\text{SO}_4)_2(\text{OH})_2 \cdot 3\text{H}_2\text{O}$

The members of this group are brownish red basic hydrous iron sulphates, in one of which, amaranite, dehydration data¹ indicate that the water is given off in three stages. The three molecules most loosely held go off below 100° , the next most loosely held above 100° and below red heat, and the hydroxyl at a higher temperature. The formulae are, accordingly, written to indicate these various kinds of water. On dehydration, when exposed to air, hohmannite apparently loses the four loosely held molecules of water and forms what is here called metahohmannite. In this respect it differs from amaranite, which is much more stable under atmospheric conditions. At Chuquicamata a fresh surface of hohmannite alters on exposure in about twenty seconds.

Amarantite is characteristically found in radiating or matted acicular crystals. Hohmannite may be distinguished by the rapidity of its alteration, and metahohmannite is always a powdery alteration product.

A comparison of the optical properties of these three minerals is given below.

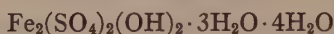
	Hohmannite	Amarantite	Metahohmannite
α	1.559	1.516	1.709
β	1.643	1.598	1.718
γ	1.655	1.621	1.734
2V	(-) 40°	(-) 30°	+
disp.	$r > v$ extreme	$r < v$	
Pleochroism	X = very pale yellow	colorless	pale yellow
	Y = pale greenish yellow	pale yellow	reddish yellow
	Z = dark greenish brown	reddish brown	reddish brown
Extinction on {010}	23°	47°	

In addition to the three species here mentioned, two other minerals, castanite² and paposite,² have been considered authentic species belonging to this group.

Castanite as originally described was given the composition $\text{Fe}_2(\text{SO}_4)_2 \cdot (\text{OH})_2 \cdot 3\text{H}_2\text{O} \cdot 4\text{H}_2\text{O}$, which corresponds to the hohmannite composition. Later³ it was considered to be identical with amarantite, and recently⁴ it has been proposed that this mineral is a valid species. However, a proposal that castanite is neither valid nor the same as amarantite has most recently been made⁵ on the basis of its physical similarity to hohmannite. With the last opinion the writer is in agreement, having arrived at this conclusion independently.

Paposite was originally given a composition corresponding to the formula $\text{Fe}_4(\text{SO}_4)_3(\text{OH})_6 \cdot 7\text{H}_2\text{O}$. However, the material from the type locality, preserved in a glass case at the University of Chile, appears to be, by inspection, amarantite. All of the so-called paposite in the collection of the National Museum at Santiago, Chile, is likewise amarantite. The original analysis, with 30 per cent of impurities, cannot be considered as adequate proof of the validity of this mineral.

Hohmannite



Crystallography: Triclinic. No crystals of this mineral were available for study.

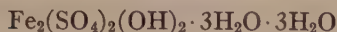
Optical properties: Color, light amaranth-red to chestnut-brown. Transparent to translucent.

	$n(\text{Na})$	
X = very pale yellow	$\alpha = 1.559$	negative
Y = pale greenish yellow	$\beta = 1.643$	$2V = 40^\circ$
Z = dark greenish brown	$\gamma = 1.655$	$r > v$ extreme

With only cleavages for orientation the optical orientation could not be worked out with any degree of certainty. The {010} cleavage yields a slightly off-center optical axis figure. Hohmannite can be distinguished from amarantite by the extinction on {010}. In hohmannite $Y \wedge [001] = 23^\circ$; in amarantite $Y \wedge [001] = 47^\circ$.

Chemistry: The composition of this mineral is not well established. The formula most suited to the analyses⁶ is that given above. The so-called castanite is in good agreement with the formula.

Hohmannite is always intimately associated with chalcantite and picromerite. The chalcantite is an earlier mineral and is believed to be formed from an earlier iron-chalcantite (pisanite?). It is usually in small, brilliant crystals showing a number of faces. Hohmannite is later than both fibroferrite and copiapite and earlier than amarantite. As stated before, it is an extremely unstable mineral, especially in a dry atmosphere, and readily dehydrates to the four hydrate mineral (meta-hohmannite).

Amarantite

Small crystals of excellent quality were available for the crystallographic and optical study. The triclinic character of the mineral was confirmed. Two new forms were established, using the elements of Penfield.

Crystallography: Triclinic

$$a:b:c=0.7692:1:0.5738; \alpha=95^\circ 38\frac{1}{2}', \beta=90^\circ 23\frac{1}{2}'; \gamma=97^\circ 13'$$

$$p_0:q_0:r_0=0.7484:0.5784:1; \lambda=84^\circ 17', \mu=88^\circ 53'; \nu=82^\circ 42\frac{1}{2}'$$

$$p_0'=0.7522, q_0'=0.5813; x_0'=0.0069, y_0'=0.1004.$$

New Forms:

	Measured		Calculated	
	ϕ	ρ	ϕ	ρ
320	$58^\circ 56'$	$90^\circ 00'$	$57^\circ 05'$	$90^\circ 00'$
301	$77\ 30$	$66\ 17$	$80\ 11\frac{1}{2}$	$66\ 14\frac{1}{2}$

These two forms are weak and not in good position so that they must be regarded as uncertain.

Optical properties: Color, amaranth-red. Transparent.

	ϕ	ρ	$n(\text{Na})$	
α =colorless	82°	72°	1.516	Negative
β =pale yellow	178°	68°	1.598	$2V=30^\circ$
γ =reddish brown	-44°	29°	1.621	$r < v$, horizontal

Chemistry: Amarantite has the composition $\text{Fe}_2(\text{SO}_4)_2(\text{OH})_2 \cdot 3\text{H}_2\text{O} \cdot 3\text{H}_2\text{O}$. This composition is well established, although a recent analysis indicated somewhat less water. This was perhaps due to some dehydration of the material which had been collected some fifty years before the analysis was made.

Occurrence: Found in the oxidized portions of massive quartz-pyrite veins at Chuquicamata and Quetena. Always found associated with hohmannite and usually with fibroferrite. Amarantite occurs along the walls of small sulphate veins with the centers usually occupied by hohmannite and fibroferrite or in crystalline masses within the hohmannite. It commonly forms in chalcantite or pisanite and develops the characteristic acicular crystals in either medium. It is less commonly associated with fibroferrite than is hohmannite. It is clearly later than all these minerals in period of formation. The only data on its sequence relationships are derived from the statement by R. Scharizer⁷ that it is later in formation than copiapite. Scharizer worked with the system $\text{Fe}_2\text{O}_3\text{-SO}_3\text{-H}_2\text{O}$ and found that when the ratio $\text{SO}_3/\text{Fe}_2\text{O}_3$ was less than 2.5 a mixture of copiapite and amarantite formed but with a ratio equal to 2.5 only copiapite formed. Posnjak and Merwin⁸ working with the

same system between the temperatures 200°C. to 50°C. did not obtain any amarantite, and at 50° found that copiapite formed with concentrations between 2.74 and 3.66, and below 2.69 no copiapite was formed. There is some question regarding the state of equilibrium of Scharizer's solutions. Posnjak and Merwin failed to find amarantite, fibroferrite and hohmannite. On the basis of these data can we assume that these three minerals form from solutions not in equilibrium?

Metahohmannite



This mineral is the dehydration product of hohmannite and has been found only as an orange powdery material in association with that mineral. Analyses have been made⁹ on this dehydrated substance, but it has been heretofore unnamed.

The optical properties were first measured in the course of this study. They are:

$\alpha = 1.709 = \text{pale yellow}$

$\beta = 1.718 = \text{reddish yellow}$

$\gamma = 1.734 = \text{reddish brown}$

The loss of about half the water (molecularly) has increased the refractive indices greatly over those of hohmannite.

REFERENCES. ¹ Scharizer, *Zeits. Krist.*, vol. 65, p. 335, 1927.

² Darapsky, *N. Jb. Min.*, 1, p. 49, 1890.

³ Linck, in Hintze, vol. 1, p. 4426, 1929.

⁴ Rogers *Am. Mineral.*, vol. 16, p. 396, 1931. The material called castanite by Bandy *Am. Mineral.*, vol. 17, p. 534, 1932, has since been re-examined and proved to be amarantite.

⁵ Ungemach, *Bull. Soc. Min.*, vol. 58, p. 97, 1935.

⁶ Analysis on original material by Frenzel, *Minn. Mitt.*, vol. 9, pp. 398 and 423, 1887; also Frenzel, *Min. Mitt.*, vol. 11, p. 215, 1890; Ungemach, 1935. Analyses on "castanite" by Darapsky, 1890, and Ungemach, 1935.

⁷ Scharizer, in Doelter, 4, 2, 574, 1929.

⁸ Posnjak and Merwin, *Jour. Am. Chem. Soc.*, vol. 44, p. 1965, 1922.

⁹ Mackintosh, 1889, and Ungemach, 1935.

Fibroferrite



Fibroferrite was identified from physical and optical properties and from older analyses made at Chuquicamata. The color ranged from grayish white in efflorescent crusts to a silky greenish gray on fresh

fractures of the massive mineral. The following optical properties were determined on fresh material:

	<i>n</i>
α —colorless	1.513
β —colorless	1.535
γ —pale brownish yellow	1.571

After a short exposure to air the mineral dehydrates into a soft incoherent mass of radiating fibers.

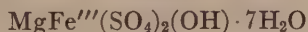
At Chuquicamata it is commonly associated with hohmannite and amarantite, being earlier than either of these minerals. In one of the more massive occurrences, chalcantite is a common associate but age relationships could not be determined. At Quetena it occurs as a late efflorescence on the walls of workings and in cracks in some of the massive minerals.

Voltaite

Voltaite was determined on the basis of optical properties. The Alcaparrosa voltaite is leek-green in crushed fragments. It is isotropic with an index of 1.608. Slight anisotropism was observed.

This is not an abundant mineral at Chuquicamata, being confined to the areas of massive pyrite veins and commonly associated with coquimbite. From field relations it appears to be earlier than metavoltine although the minerals have not been observed intimately associated. It is later than coquimbite. At Quetena it occurs massive in massive coquimbite in the bottom of the pit. Its paragenetic relationships were not clear. Voltaite occurs in small crystals at Alcaparrosa imbedded in pickeringite and alums.

Botryogen



A number of minerals have been described and given species names that have later been proved to belong to this species. There are two reasons for this. The original and early descriptions of botryogen were inaccurate and the descriptions and identifications of synonymous species were either inaccurate or, in the case of palacheite, more accurate than the original description of botryogen proper.

During this study the writer has concluded that quetenite, rubrite, idrizite, palacheite and the mineral called kubeite should all be included under botryogen as synonyms. All of these minerals have been recognized as thus related by one writer or another. Positive identification can be made on quetenite.

Crystallography:¹Monoclinic; prismatic— $2/m$

$$\begin{aligned}
 a:b:c &= 0.5893:1:0.3996 & \beta &= 100^{\circ}01' \\
 p_0:q_0:r_0 &= 0.6781:0.3935:1 & \mu &= 79^{\circ}59' \\
 r_2:p_2:q_2 &= 1.4747:1.7232:1 \\
 p_0' &= 0.6886, q_0' = 0.3996; x_0' = 0.1766
 \end{aligned}$$

Forms	ϕ	ρ	ϕ_2	$\rho_2=B$	C	A
<i>b</i> 010	0°00'	90°00'	—	0°00'	90°00'	90°00'
<i>a</i> 100	90 00	90 00	0°00'	90 00	79 59	0 00
<i>e</i> 270	26 13	90 00	0 00	26 13	85 35½	63 47
<i>k</i> 130	29 52½	90 00	0 00	29 52½	85 02	60 07½
<i>f</i> 250	34 34½	90 00	0 00	34 34½	84 20	55 25½
<i>l</i> 120	40 45	90 00	0 00	40 45	83 29	49 15
<i>h</i> 350	45 57½	90 00	0 00	45 57½	82 49	44 02½
<i>t</i> 450	54 02½	90 00	0 00	54 02½	81 54½	35 57½
<i>m</i> 110	59 52½	90 00	0 00	59 52½	81 21	30 07½
<i>i</i> 210	73 49	90 00	0 00	73 49	80 23	16 11
<i>F</i> 310	79 03	90 00	0 00	79 03	80 10	10 57
<i>p</i> 011	23 50½	23 36	79 59	68 31	21 29	80 41
<i>s</i> 021	12 27½	39 18	79 59	51 48	38 12	82 08½
<i>P</i> 031	8 23	50 28	79 59	40 16	49 44	83 33
<i>d</i> 101	90 00	40 54	49 06	90 00	30 53	49 06
<i>o</i> 101	—90 00	27 04	117 04	90 00	37 05	117 04
<i>r</i> 111	65 14	43 39	49 06	73 11½	34 45½	51 11½
<i>z</i> 221	67 17½	64 13	27 38	69 39½	55 03½	33 50
<i>n</i> 111	—51 58½	32 58½	117 04	70 25	41 16½	115 23
<i>D</i> 121	47 18	49 41	49 06	58 52	42 43½	55 55
<i>u</i> 131	35 51	55 56	49 06	47 49	50 30½	60 58½
<i>w</i> 141	28 27	61 11	49 06	39 37	56 49½	65 19½
<i>v</i> 121	—32 35½	43 29½	117 04	54 33½	49 27½	111 45½
<i>q</i> 131	—23 05	52 30	117 04	43 08	56 57	108 07½
<i>x</i> 171	—10 21	70 37½	117 04	21 52½	72 42½	99 45½
<i>y</i> 211	—75 35	58 04½	147 15	77 48	67 48½	145 17½

Crystals of botryogen were first described by Haidinger¹⁵ and have been frequently studied by later workers. All the early work suffered from the poor quality of the crystals available. Eakle¹³ obtained the first reliable results on the material which he named palacheite but which proved to be botryogen. In this study excellent crystals of quetenite have been measured both by the author and by Dr. Berman, and

they have finally established its identity with botryogen. The results of these studies are contained in the table of forms observed by each, together with a column showing symbols of each known form in the new position.

Eakle	BOTRYOGEN: OBSERVED FORMS.			Palache New Symbol
	Berman	Bandy		
<i>c</i> 001	<i>c</i>	<i>c</i>		<i>o</i> 101
<i>b</i> 010	<i>b</i>	<i>b</i>		<i>b</i> 010
<i>a</i> 100	—	—		<i>a</i> 100
—	—	<i>e</i> 270		<i>e</i> 270
—	<i>k</i> 130	<i>k</i>		<i>k</i> 130
—	—	<i>f</i> 250		<i>f</i> 250
<i>l</i> 120	<i>l</i>	<i>l</i>		<i>l</i> 120
—	—	<i>h</i> 350		<i>h</i> 350
<i>t</i> 450	—	—		<i>t</i> 450
<i>m</i> 110	<i>m</i>	<i>m</i>		<i>m</i> 110
—	—	<i>i</i> 210		<i>i</i> 210
—	—	<i>F</i> 310		<i>F</i> 310
<i>n</i> 011	<i>n</i>	<i>n</i>		<i>n</i> 111
<i>o</i> 021	<i>o</i>	<i>o</i>		<i>v</i> 121
—	—	<i>q</i> 031		<i>q</i> 131
—	—	<i>x</i> 071		<i>x</i> 171
<i>d</i> 201	<i>d</i>	<i>d</i>		<i>d</i> 101
<i>p</i> 111	<i>p</i>	<i>p</i>		<i>p</i> 011
<i>s</i> 121	<i>s</i>	<i>s</i>		<i>s</i> 021
—	—	<i>P</i> 131		<i>P</i> 031
—	<i>r</i> 211	<i>r</i>		<i>r</i> 111
—	—	<i>D</i> 221		<i>D</i> 121
—	<i>u</i> 231	<i>u</i>		<i>u</i> 131
—	<i>w</i> 241	<i>w</i>		<i>w</i> 141
—	<i>z</i> 321	<i>z</i>		<i>z</i> 221

Habit: Prismatic [001]; smaller crystals long prismatic, large crystals short prismatic; common forms *o b m l n*; vertical zone striated [001]. In the larger short crystals *o* is the dominant form, often striated [100].

Twinning: Not observed.

Cleavage: {010} perfect; {110} good.

Physical Properties: Fracture conchoidal and interrupted, brittle.

G 2.10, H 2.0—2.5. Luster vitreous.

Optical Properties: Color light to dark orange-red. Transparent to translucent.

$\alpha = 1.523$	$X = b$	colorless to pale brown	Biaxial positive
$\beta = 1.530$		cinnamon brown	$2V = 42^\circ$
$\gamma = 1.582$	$Z \wedge c = +12^\circ$	golden yellow	$r > v$ strong

Composition: $\text{MgFe}'''(\text{SO}_4)_2(\text{OH}) \cdot 7\text{H}_2\text{O}$

ANALYSIS BY HENDERSON*		THEORETICAL COMPOSITION
(Quetenite)		
Fe_2O_3	19.73	19.28
MgO	9.40	9.64
SO_3	38.45	38.55
H_2O	32.00	32.53
Total	100.18	100.00

* U. S. National Museum. Unpublished.

Difficultly soluble in water with precipitation of iron hydroxide. Soluble in dilute acids.

Pyrognostics: B.B. brown to black. Exfoliates in flame. Closed tube, yields copious water.

Occurrence: Botryogen is common at Chuquicamata intimately associated with hohmannite and amarantite. At Alcaparrosa it occurs near the surface associated with copiapite in smaller veins. Botryogen is not associated with the more massive and purer occurrences of iron sulphates.

Botryogen (quetenite) occurs at Quetena in large masses, characteristically in halos of coarse radiating crystals about a center of copiapite. The crystals radiate outwardly from the copiapite core. Often these nodules of copiapite-botryogen show rough cracks about the peripheries, which often contain fibres of pickeringite. Massive veins of pickeringite cut the botryogen in many cases.

The sequence relationship that can be definitely established is,

Pickeringite	$\text{MgAl}_2(\text{SO}_4)_4 \cdot 22\text{H}_2\text{O}$
Botryogen	$\text{Mg}_2\text{Fe}_2(\text{SO}_4)_4(\text{OH})_2 \cdot 14\text{H}_2\text{O}$
Parabutlerite	$\text{Fe}(\text{SO}_4)(\text{OH}) \cdot 2\text{H}_2\text{O}$
Amarantite	$\text{Fe}(\text{SO}_4)(\text{OH}) \cdot 3\text{H}_2\text{O}$
Hohmannite	$\text{Fe}_2(\text{SO}_4)_2(\text{OH})_2 \cdot 7\text{H}_2\text{O}$
Copiapite	$\text{Fe}_4(\text{SO}_4)_6(\text{OH})_2 \cdot 16\text{H}_2\text{O}$

From these data it is apparent that the introduction of magnesia causes a departure from the sequence of the pure iron sulphates. The botryogen, while basic, is less basic than the parabutlerite and the pickeringite, the last formed, is a normal sulphate.

The relations of the various substances, all believed to be identical with botryogen, is brought out in the following table of analyses.

Rubrite answers the description of quetenite and, since it was identified from the analysis of an impure material, there can be little question but that it belongs here.

The original analysis of quetenite from Quetena (Salvador Mine)⁵ was made on impure material, evidently a mixture of quetenite and some iron sulphate. Rubrite was described from the Rio Loa by Darapsky² and earlier kubeite from the same locality and by the same writer.³ These are both impure mixtures of botryogen and other sulphates. Analyses of these minerals as well as other analyses of this species are quoted here for comparison. Quetenite was first recognized as a synonym of botryogen by Larsen and Berman⁴ on the basis of similar optical properties. In the course of this investigation an analysis of typical quetenite was made and it was found to be identical with botryogen. Their crystallographic identity was also established.

ANALYSES OF BOTRYOGEN							
	1	2	3	4	5	6	7
MgO	6.65	7.40	7.31	10.21	5.69	6.18	3.59
Fe ₂ O ₃	18.73	16.69	19.60	20.63	26.50	26.64	20.50
SO ₃	37.64	37.00	37.78	38.10	36.53	32.42	40.95
H ₂ O	31.04	34.10	31.39	29.47	30.90	31.04	30.82
FeO	0.53	2.24	0.38				4.12
CaO		1.06			2.91		
MnO		1.93	0.44				
ZnO	4.82		2.50				
Al ₂ O ₃						2.73	
P ₂ O ₅						0.11	
Insol.	0.27	0.30	0.21				
Total	99.68	100.72	99.61	98.41	102.53	99.12	99.98
	8	9	10	11	12	13	14
MgO	5.92	9.40	9.35	5.62	7.8	4.51	9.95
Fe ₂ O ₃	22.70	19.73	19.51	18.22	19.3	8.70	19.81
SO ₃	37.37	38.45	38.37	41.15	36.4	33.94	39.48
H ₂ O	34.01	32.00	32.28	27.64	33.7	40.80	30.76
CaO				4.10	0.1		
Fe(Mn)O						3.10	
Al ₂ O ₃				3.01	abs.	8.59	
Insol.					2.7		
Total	100.00	100.18	99.51	99.84	100.0	99.64	100.00

1-4. Botryogen, 1. Cleve,⁶ 2. Hockauf, analyst.⁷ 3. Mauzelius, anal.⁸ 4. Ungemach, anal.⁹

5-7. Botryogen? 5. Berzelius, anal.¹⁰ 6. Ungemach, anal.¹¹ 7. Blaas, anal.¹²

8. Quetenite. Frenzel, anal.⁵ 9. Quetenite. Henderson, U. S. Nat. Museum, unpublished anal.

10. Palacheite. Eakle, anal.¹³
11. Rubrite. Darapsky, anal.²
12. Kubeite. Darapsky, anal.³
13. Idrizite. Schrauf, anal.¹⁴
14. Quetenite. Anal. of the Chile Exploration Co., Chemical Laboratory. Through the courtesy of O. W. Jarrell.

REFERENCES. ¹ The elements and angles of this table are derived from the observations of Berman¹⁶ on quetenite. They were very close to Eakle's¹³ observations on botryogen (palacheite). Eakle's elements give an unsymmetrical distribution of the forms and have been modified by Palache according to the transformation Eakle→Palache $\bar{1}0\bar{1}/0\bar{1}0/001$.

² Darapsky, *N. Jb. Min.*, vol. 1, p. 65, 1890.

³ Darapsky, *N. Jb. Min.*, vol. 1, p. 163, 1898.

⁴ Larsen and Berman, *Bull.* **848**, U.S.G.S., 1934.

⁵ Frenzel, *Min. Mitt.*, vol. 11, p. 217, 1890.

⁶ Cleve, *Upsala Un. Arsskrift*, vol. 22, 1862.

⁷ Hockauf, *Zeits. Krist.*, vol. 12, p. 251, 1886.

⁸ Mauzelius, *Geol. För. Förh.*, vol. 17, p. 311, 1895.

⁹ Ungemach, *Bull. Soc. Fr. Min.*, vol. 57, p. 97, 1935.

¹⁰ Berzelius, *Afh. i. Fys.*, vol. 4, p. 307, 1815.

¹¹ Ungemach, *Bull. Soc. Fr. Min.*, vol. 29, p. 271, 1906.

¹² Blaas, *Sitzber. Wiener Ak., I Abt.*, vol. 8, pp. 87, 161, 1883.

¹³ Eakle, *Bull. Univ. Calif.*, vol. 3, p. 231, 1903.

¹⁴ Schrauf, *Jb. d. geol. R. A. Wien*, vol. 41, p. 379, 1891.

¹⁵ Haidinger, *Pogg.*, vol. 12, p. 491, 1828.

¹⁶ Berman, Unpublished data on botryogen (quetenite).

Alunite

Alunite occurs at Chuquicamata as a supergene vein mineral and in the oxidized gossans of the larger pyrite veins. It commonly shows the characteristic "hopper structure." In veins associated with antlerite it is the earlier mineral. In the oxidized gossans it was only observed altered to jarosite. The writer was never able to separate the mineral in order to determine whether it was the potassium or sodium variety of alunite.

JAROSITE GROUP

Jarosite and natrojarosite are relatively common minerals in all of these deposits. They are late minerals as a rule and serve well as key minerals for the later part of the mineral sequence.

Jarosite



Jarosite is common at Chuquicamata in fibrous and massive aggregates and in minute tabular crystals. It occurs throughout the deposit but is most common in massive form in the central part. A micaceous variety with the external appearance of argento-jarosite was known as

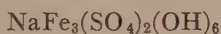
apatelite¹ locally. The jarosite at Chuquicamata carries a small but variable percentage of silver as a rule and argento-jarosite may be a rare mineral of the deposit. All of the jarosite examined in this study was either the potassium or sodium variety. A rare form of jarosite is a variety pseudomorphic after either alunite or natroalunite. The jarosite has replaced the alunite, preserving the "hopper crystal" structure of the original mineral. The jarosite shows an average index, $n = 1.816$.

Jarosite occurs in minute crystals and crystalline and granular crystals at Quetena and Alcaparrosa. The mineral has an index $n = 1.818$ at both places. The jarosite at Alcaparrosa commonly shows under the microscope a slight divergence of the optic axes.

Jarosite commonly forms at the end of the iron sulphate period and before the copper sulphate period. Reversals of this order were recorded during the study, but the sequence relationships were not always definite.

REFERENCE. ¹ Meillet, *Ann. des Mines*, vol. 3, p. 808, 1841.

Natrojarosite



The tiny brilliant cinnamon brown crystals of natrojarosite at Chuquicamata afforded an opportunity to study the crystallography, and especially the twinning of this species. An explanation of the previously noted anomalous optical behavior is given, and other new data are here presented.

Crystallography:

Orthorhombic (Pseudorhombohedral)

$a:b:c = 1.732:1:2.252$		$p_0:q_0:r_0 = 1.300:2.252:1$				
$q_1:r_1:p_1 = 1.732:0.769:1$		$r_2:p_2:q_2 = 0.444:0.577:1$				
Forms	ϕ	$\rho = C$	ϕ_1	$\rho_1 = A$	ϕ_2	$\rho_2 = B$
<i>c</i> 001	—	0°00'	0°00'	90°00'	90°00'	90°00'
<i>m</i> 110*	60°00'	90 00	90 00	60 00	0 00	30 00
<i>u</i> 101	90 00	52 26	0 00	37 34	37 34	90 00

* Noted only as a twin plane.

Form	Measured No. of Faces	Range ρ
<i>u</i> 101	29	52°06'–52°57'

Habit: Commonly in cuboid trillings; common forms: *c*, *u*.

Twins: In trillings; twin plane (110).

Physical properties: Fracture conchoidal, brittle; $H=3$. Luster vitreous.

Optical properties: Color, cinnamon brown. Basal section divided into three biaxial segments. Biaxial negative, $2V$ small; $\beta=1.826$. $X=c$; $Y=a$.

The first observation that natrojarosite was not uniaxial, and that it was made up of biaxial segments, was on material from Schlaggenwald.¹ Later² the same optical effects were noted on specimens from Buxton Mine, North Dakota. The same effect, but less distinct, has been noted on other members of the jarosite group.³

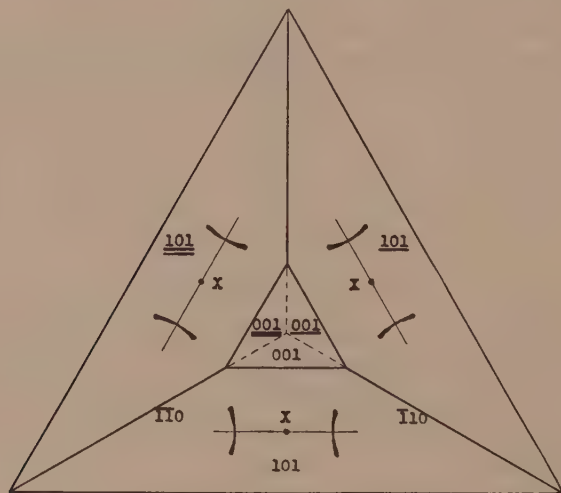


FIG. 7. Sketch showing optical orientation in the orthorhombic trillings of natrojarosite.

The optical orientation on the various segments is illustrated in Fig. 7, where X emerges sensibly normal to each of the (001) faces, the latter being co-planes in the twin. The plane of the optic axes is parallel, in each case, to (100) . Under these circumstances, the smaller $2V$ is, the more difficult it becomes to recognize the segmentation of the twins, for, if $2V=0$, no birefringence would be noted and the twinning could not be detected under the microscope. The potassium members of the group have presumably a smaller $2V$ because the effect is less marked than in natrojarosite, and the Chuquicamata natrojarosite exhibits the twinning best because it is the most sodic of any yet found.⁴

Chemistry: A basic sodium ferric sulphate, $\text{NaFe}_3(\text{SO}_4)_2(\text{OH})_6$, with small amounts of potassium sometimes substituting for the sodium.

ANALYSIS BY F. A. GONYER

	Per Cent	Molecular Ratios	
Na ₂ O	5.51	.091	1×.091
K ₂ O	0.15		
Fe ₂ O ₃	48.08	.302	3×.101
SO ₃	34.65	.433	4×.108
H ₂ O	11.83	.659	6×.110
Total	100.22		

Occurrence: The mineral was first described,⁵ but not named, from the Buxton Mine, Lawrence County, North Dakota. Later⁶ it was found at Soda Springs Valley, Nevada, and at Cook's Peak, New Mexico, and was given the name natrojarosite.

At Chuquicamata natrojarosite is associated with chalcantite, kroehnkite and sulphur. It is a late mineral, forming after most of the iron sulphates and before most of the copper sulphates.

REFERENCES. ¹ Slavik, *Zeits. Krist.*, vol. 39, p. 297, 1904, stated that the natrojarosite showed six segments in the basal section, and that the axial plane is (010). These data are not in agreement with the writer's.

² Cesaro, *Bull. Ak. Roy. Belge*, 138, 1905.

³ Larsen and Berman, *Bull.*, 848, *U. S. Geol. Survey*, 1934.

⁴ For other analyses see Hillebrand and Penfield *Am. J. Sc.*, vol. 14, p. 211, 1902; also Dana, *System*, Ap. III.

⁵ Headen, *Am. J. Sc.*, vol. 46, p. 24, 1893.

⁶ Hillebrand and Penfield, *Am. J. Sc.*, vol. 14, p. 211, 1902.

Ungemachite

This mineral, discovered in the course of this investigation, has been described in detail by Peacock and Bandy in a recent paper.¹ The following abstract of properties is taken from that paper.

Crystallography: Hexagonal, rhombohedral— $\bar{3}$. $a:c = 1:2.2966$, $\alpha = 62^\circ 51\frac{1}{2}'$; $p_0:r_0 = 2.6519:1$, $\gamma = 108^\circ 15\frac{1}{2}'$.

Forms: Numerous, the habit dominantly rhombohedral with $r(10\bar{1}1)$, $M(01\bar{1}2)$, $p(11\bar{2}3)$, and the base $c(0001)$.

Structure cell: Rhombohedral: $a_0 = 10.84 \pm 0.02\text{\AA}$, $c_0 = 24.82 \pm 0.03\text{\AA}$. $a_0:c_0 = 1:2.290$. Contains $\text{Na}_8\text{K}_3\text{Fe}(\text{SO}_4)_6 \cdot 10\text{H}_2\text{O}$.

Cleavage: Perfect, basal.

Physical properties: $H = 2\frac{1}{2}$. $G = 2.287 \pm .003$ (Berman).

Optical properties: Colorless, transparent. Uniaxial negative. $\omega = 1.502$, $\epsilon = 1.449$.

Chemical composition:

ANALYSIS BY F. A. GONYER

Na ₂ O	21.61
K ₂ O	11.35
Fe ₂ O ₃	7.69
SO ₃	40.23
H ₂ O	16.69
N ₂ O ₅	tr.
Insol.	2.07
Total	99.64

Composition as written above is not homologous with any known natural or artificial salt.

Occurrence: Ungemachite occurs in granular vein fillings and lining small vugs in massive jarosite and metasideronatrite. The mineral is very scarce in the material collected. The name is in honor of the late Henri Ungemach, mineralogist of Strasbourg.

REFERENCE. ¹ Peacock and Bandy, *Am. Mineral.*, vol. 23, p. 314, 1938.

Clino-Ungemachite

Clino-ungemachite¹ is a monoclinic mineral closely similar in appearance and occurrence to ungemachite from which it was distinguished only by goniometric measurements. The divergence of angles from rhombohedral symmetry is slight, and it is presumed that the composition of this substance is close to that of ungemachite. But as only six minute crystals were found its nature is still uncertain.

REFERENCE. ¹ Peacock and Bandy, *Am. Mineral.*, vol. 23, p. 314, 1938.

MOLYBDATE

Lindgrenite

Lindgrenite¹ is monoclinic, holohedral. $a:b:c=0.5941:1:0.5124$; $\beta=92^\circ 12'$. The crystals are green and transparent, tabular parallel to (010), which is a perfect cleavage. Unit cell: $a_0=8.45$, $b_0=14.03$, $c_0=7.04$; $\beta=92\frac{1}{2}^\circ$; containing $\text{Cu}_{12}(\text{MoO}_4)_8(\text{OH})_8$. $\text{H}=4\frac{1}{2}$. $\text{G}=4.26$. Biaxial negative; $Z=b$; $X:c=+7^\circ$. $\alpha=1.930$, $\beta=2.002$, $\gamma=2.020$; $2V=71^\circ$; $r>v$. Analysis: CuO 40.62, MoO_3 50.97, H_2O 3.30, Fe_2O_3 1.43, Insol. 3.34; Sum 99.66; giving the above formula. Soluble in HCl and in HNO_3 .

This unusual mineral, the first known molybdate of copper was collected by the writer during his residence at Chuquicamata. It occurs associated with antlerite and iron oxide in massive quartz veins on the western side of the deposit. The mineral is rather common, although fine

crystallized specimens are rare. It occurs along the edges of the larger quartz veins. In this connection it is possibly significant that the molybdenum in the smaller "lacing veinlets" of quartz occurs along or near the edges of the veins. Antlerite follows the lindgrenite and replaces it.

REFERENCE. ¹ Palache, *Am. Mineral.*, vol. 20, p. 484, 1935.

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NATURAL AMALGAMS

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Amalgam is a word of mongrel (Arabic-Greek) origin, the history of which is obscure. However, it has been in use since at least the twelfth century, and its meaning has been clear in the earliest references, as given by Mellor (1923). Present-day chemists and metallurgists use the word in the same sense as did the early alchemists, that is, as a general term referring to the solution of metals in mercury, or the combination of the metals with mercury.

Early mineralogical works of Cronstedt (1758) and Romé de Lisle (1783) used the term *amalgam* in describing the natural mercury alloys, and, because the natural alloy most abundant is silver-amalgam, the term has finally become the name of a supposed mineral species (Dana, 1892). However, aside from the inappropriate usage of a general term for specific designation, the name should no longer be used to designate this supposed mineral species, because silver-amalgam in nature embraces at least two separate minerals, differing widely in most of their properties, as will be shown below. It is suggested here that the word *amalgam* should be used in the mineralogical literature in the same sense that it is used by the metallurgists, and that specific natural alloys of the metals with mercury be given species or varietal names. In the following section redescriptions of the silver-amalgams are given, and the suggested changes in nomenclature are incorporated.

SILVER-AMALGAMS

In a recent study of the artificial system Ag-Hg, Murphy (1931) showed that there are at least three well-defined phases present, as follows: (1) a mercurial silver (α -phase) with Hg entering into solid solution in the face-centered silver lattice to the extent of about 45 per cent, with a consequent distension of the cell edge from 4.077Å to 4.175Å; (2) a close-packed hexagonal phase (β -phase) formed in the region of 60 per cent Hg; (3) a body-centered cubic modification (γ -phase) with $a_0=10.0\text{\AA}$ and a composition of 70 to 71 per cent Hg.¹

Of the three alloys found in the artificial system, probably only two occur in nature, the α and γ phases of Murphy. The α -phase is a mer-

¹ There is no unanimous agreement among the various recent workers about the composition of this last-mentioned alloy. Westgren (1931) and Stenbeck (1933) are of the opinion that the γ -phase is similar to γ -brass and a number of other alloys of that same type, and it should consequently have a 52-atom unit cell, which would give the alloy a composition $4\text{Ag}_5\text{Hg}_3$. However, Murphy's work indicates a unit of somewhat fewer atoms. The mineralogical evidence given here tends to favor Murphy's interpretation.

curial silver, and the natural occurrences of this substance should be considered as varieties of silver. Thus *arquerite*, *kongsbergite* and *bordosite* are varietal names under *silver*. Mercurial silver is usually massive or in dull crystals of the typical silver habits; it is malleable, and contains less than about 45 per cent mercury.

Three analyses of natural amalgams are in the range between the α - and γ -phases. Of these, the earliest (Analysis 3 of Table 1) was made in 1795 and the silver was only roughly determined; another is by Domeyko (1879), in 1862, on material of doubtful homogeneity; the third is on Sala material by Nordstrom (1881). Two more recent Sala analyses (see Table 1) indicate that this material certainly contains the γ -phase.

The γ -phase is represented in nature by well-crystallized material with a shiny metallic luster. The crystals are widely different in most of their properties from the variety here designated mercurial silver. The following is a description based on crystals from Moschellandsberg (one of the earliest reported occurrences of natural amalgam).

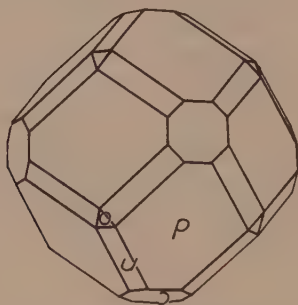


FIG. 1. Moschellandsbergite.

Crystallography: The previously established data, as given by Goldschmidt (1913), for crystals from Moschellandsberg (Fig. 1) have been verified, as follows:

Isometric—I-hexoctahedral— $4/m \bar{3} 2/m$

Forms: $c(001)$, $a(013)$, $e(012)$, $d(011)$, $n(112)$, $p(111)$, $u(122)$, $x(123)$.

An x -ray powder picture of material used for the crystallographic and chemical study verified the findings of Preston (1931) on the artificial preparations; that is, the powder picture could be indexed as a body-centered cubic lattice with $a_0 = 10.1\text{\AA}$. The space group is $Im \bar{3}m$,² and the unit cell contains $\text{Ag}_{20}\text{Hg}_{30}$.

² $h+k+l$ all even, hhl all missing, okl with $k+l$ even; checked by zero and first layer Weissenberg photographs.

The crystal habit is dominantly dodecahedral, frequently modified by $c(001)$ and $n(112)$, so that the morphological development is consistent with the space group, according to the rules of Donnay (1937).

Physical Properties: This substance is easily distinguished from mercurial silver in its physical properties. The cleavage is distinct on $d(011)$ and $c(001)$. The fracture is conchoidal; the brittleness is such that the material crushes easily to a powder. $H=3\frac{1}{2}$. $G=13.48$ to 13.71 (13.73 calculated from x -ray data for a 52-atom cell, 13.49 calculated for a 50-atom cell). Silver white and shiny.

Chemistry: Crystals from a Moschellandsberg specimen were crushed for the chemical work. It was found that free mercury was attached to the crystal fragments. This was removed by centrifuging. Other specimens examined showed this same saturation with mercury, implying that silver-amalgams cannot retain more than the amount of mercury demanded by the formula Ag_2Hg_3 , that is, there is little or no solid solution in the system Ag_2Hg_3 -Hg, at room temperatures.

The following is a tabulation of analyses of this material, including a new analysis by Mr. F. A. Gonyer, of this laboratory, on the crystals of this study.

TABLE 1. ANALYSES.

	1.	2.	3.	4.	5.	6.	7.
Ag	25.16	27.04	36	27.5	26.48	29.91	26.39
Hg	74.84	72.94	(64)	72.5	73.44	70.44	73.61
Total	100.00	99.98	100.	100.0	99.92	100.00	100.00
G	13.73	13.48			13.71		13.49

1. Theoretical composition for Ag_2Hg_3 .
2. Moschellandsberg. Crystals freed from adhering mercury by centrifuging. Gonyer analyst.
3. Moschellandsberg. Klaproth analyst (*Beitr.*, vol. 1, p. 182, 1795—*Dana System*, p. 23, 1892).
4. Calanches near Allemont. Cordier analyst. (*J. Mines*, vol. 12, p. 1, 1802).
5. Sala. Mauzelius analyst (in Sjögren, *Geol. Fören. Förh.*, vol. 22, p. 187, 1900). Crystals.
6. Sala. Mauzelius analyst (in Sjögren). Massive. After deducting 8.89 per cent sulphide silicate impurities.
7. Theoretical composition for Ag_2Hg_3 .

Occurrence: Silver-amalgams with a composition near Ag_2Hg_3 have been found at three localities. At Moschellandsberg (Landsberg near Ober-Moschel), Bavaria, and at Sala, Sweden, fine crystals have been

found. They have also been reported and analyzed from Calanches, near Allemont, Isere, France.

Name: It is proposed that the silver amalgam having a composition near Ag_2Hg_3 , here described, be named *moschellandsbergite* after the locality at which fine crystals have been found and described.

GOLD-AMALGAM

In the artificial system Au-Hg as reviewed by Hansen (1936), there are a number of phases present, one of which, Au_2Hg_3 , corresponds in composition to the natural gold-amalgam from Colombia reported by Marchand (1848) and by Sonnenschein (1854) from the Mariposa region in California. Nothing is known of the crystallography or physical properties of these natural occurrences; but the close similarity of the formulae of this gold-amalgam and the body-centered cubic, silver-amalgam, *moschellandsbergite*, indicates that the natural occurrence probably represents a species which is the gold equivalent of this mineral. However, the writers have not been able to obtain natural crystals of the gold-amalgam and the study has not been pursued further.

PALLADIUM-AMALGAM

The mineral *potarite*, recently described by Spencer (1928), represents an alloy of palladium and mercury (Pd, Hg), but it has been shown by Cissarz (1930) that the originally described material was not homogeneous and two phases may be represented by the analyses.

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 Nordstrom (1881): *Geol. Fören. Förh.*, vol. **5**, p. 715.
 Preston (1931): In Murphy (1931).
 Sonnenschein (1854): *Zeits. Geol. Ges.*, vol. **6**, p. 243.
 Spencer (1928): *Min. Mag.*, vol. **21**, p. 297.
 Stenbeck (1933): *Zeits. anorg. Chem.*, vol. **214**, p. 16.
 Westgren (1931): *J. Inst. Metals, Proc.*, vol. **46**, p. 2, 532.

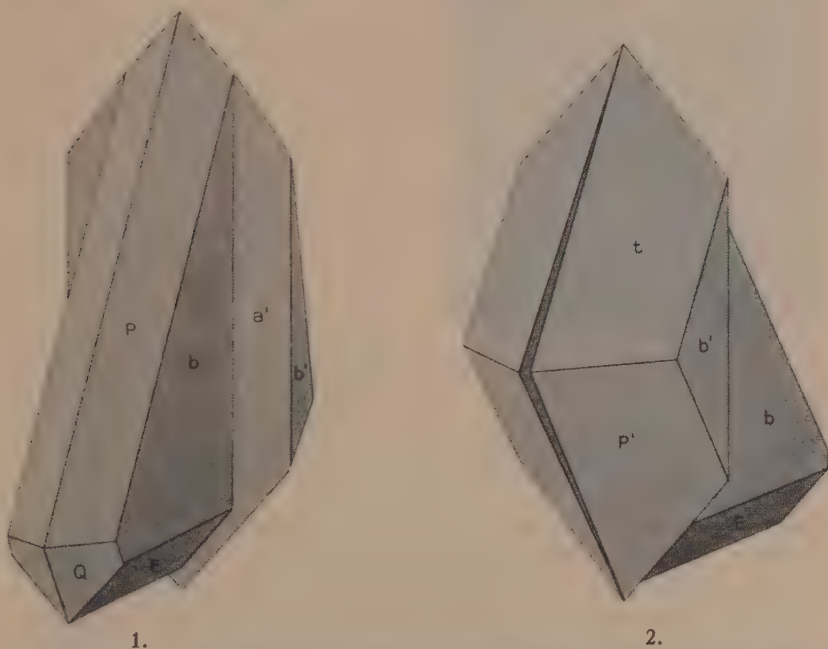
PARAHILGARDITE, A NEW TRICLINIC-PEDIAL MINERAL

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ABSTRACT

The new species, parahilgardite, found in the Choctaw Salt Dome, Louisiana, is so named because of its close similarity with hilgardite. The specimens are invariably made up of one right-hand and one left-hand individual attached to the negative end of the a -axis of a hilgardite crystal. Parahilgardite is triclinic-pedial—the second mineral to be described in this class. $a:b:c=0.5045:1:0.2783$; $\alpha=90^{\circ}00'$, $\beta=90^{\circ}00'$, $\gamma=91^{\circ}12'$. Its physical properties are identical with those of hilgardite: clear and colorless; cleavage $\{010\}$ and $\{100\}$; $H=5$, $G=2.71$. Biaxial positive, $2V=35^{\circ}$, $r>v$, $nX=1.630$, $nY=1.636$, $nZ=1.664$. The dimensions of the unit cell: $a_0=11.24\text{\AA}$, $b_0=22.28\text{\AA}$, $c_0=6.20\text{\AA}$. The chemical formula expressing the content of the unit cell can be written as: $2[\text{Ca}_8(\text{B}_6\text{O}_{11})_2 \cdot \text{Cl}_4 \cdot 4\text{H}_2\text{O}]$.

A new mineral, hilgardite, found in the Choctaw Salt Dome, Iberville Parish, Louisiana, was described recently by Hurlbut and Taylor (1937). Hilgardite was found in isolated monoclinic crystals of the domatic class, all of which presented a characteristic triangular appearance. More recently additional material from the same salt dome was sent the writer by Mr. Taylor. In this material a few single crystals were found, but



FIGS. 1 AND 2. The characteristic appearance of hilgardite-parahilgardite intergrowths. Figure 1 shows the positive end and Fig. 2 the negative end of the intergrowth.

more abundant than these were hilgardite crystals with growths at one end giving the intergrowths the appearance of twins. In endeavoring to work out the twin law, it was discovered that the optical orientation with respect to the cleavages was different in the different individuals. The supposed twin was thus found to be a parallel growth of two minerals. The name *parahilgardite* has been given to this new mineral because of its close relation to the associated hilgardite.

Parahilgardite was not found as unattached crystals, and all of it appears to have formed by growing on the earlier hilgardite. The crystals range from 0.3 mm. to 8.0 mm. in maximum dimension and are usually smaller than but proportional to the size of the attached hilgardite. An occasional crystal is found where parahilgardite has relatively large dimensions and dwarfs the associated hilgardite individual.

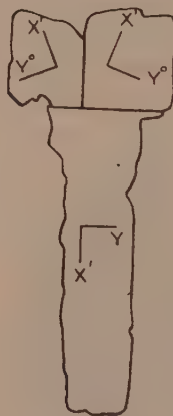


FIG. 3. Photograph of thin section cut normal to the c crystallographic axis showing the right and left hand parahilgardite individuals joined to the hilgardite. Crossed nicols. $\times 8$.

FIG. 4. The optical orientation of the three individuals shown in Fig. 3. Y° in the parahilgardite indicates the direction of Z' very close to Y .

Almost without exception parahilgardite is made up of two individuals joined to the $(\bar{1}00)$ plane of hilgardite (Figs. 2 and 3). These two individuals appear to be in twin position to one another as shown in Fig. 4. They usually are not in contact, and their orientation, therefore, is not controlled by their mutual relationship, but rather by their relation to hilgardite. The parahilgardite individuals are arranged in such a manner

that the complete intergrowth has monoclinic symmetry, thus giving further confirmation of the conclusion that hilgardite itself is monoclinic. The presence of parahilgardite always at the negative end of the a -axis of hilgardite indicates the polar nature of that axis and confirms the domatic class for hilgardite.

MORPHOLOGY

Parahilgardite is triclinic-pedial, but very closely related structurally and morphologically to hilgardite. It has been chemically attacked and the faces are universally etched, even more than those of hilgardite. Only four crystals were found whose faces would give reflections, and these were so poor that only an approximation of their position could be obtained.

Two excellent cleavages, $b\{010\}$ and $a\{100\}$ in the parahilgardite, permitted an accurate orientation of the crystals. The zone axis $[001]$ determined by these cleavages is parallel to the corresponding zone axis in hilgardite and was set vertical for crystal measurements. The two-circle measurements given in Table 1 are for the left-hand individual of parahilgardite, the one in normal position. The elements and angles in Table 2 are also for the left-hand crystal, and were calculated by using the elements derived from the x -ray measurements, since it is believed they were determined with greater accuracy than the best of the morphological measurements. The writer is greatly indebted to Mr. C. W. Wolfe for the calculation of the angles in Table 2.

TABLE 1. TWO-CIRCLE MEASUREMENTS ON FOUR CRYSTALS

Forms	No. of Faces	Measured Range		Measured Mean	
		φ	ρ	φ	ρ
\bar{b} 010	8	180°00'	90°00'	180°00'	90°00'
a 100	3	88°47'–88°49'	90 00	88 48	90 00
\bar{a} 100	4	–91 10–91 14	90 00	– 91 12	90 00
j 160	1	–17°55'	90 00	–17 55	90 00
k 120	1	–45 14	90 00	–45 14	90 00
l 120	1	–134 22	90 00	–134 22	90 00
n 160	1	–161 34	90 00	–161 34	90 00
p 121	5	–134°15'–133°49'	142°11'–141°32'	–134 02	141 50
r 161	1	–18°42'	119°30'	– 18 42	119 30
s 342	1	–123°22'	134°05'	–123 22	134 05
t 321	3	–106°46'–106°22'	62°51'–64°53'	–106 34	63 52

TABLE 2. PARAHILGARDITE. TRICLINIC; PEDIAL—1

		$a:b:c=0.5045:1:0.2783$		$\alpha=90^{\circ}00', \beta=90^{\circ}00', \gamma=91^{\circ}12'$		
		$p_0:q_0:r_0=0.5518:0.2781:1$		$\lambda=90^{\circ}00', \mu=90^{\circ}00', \nu=88^{\circ}48'$		
		$p_0'=0.5518, q_0'=0.2784; x_0'=0.00, y_0'=0.00$				
Forms		φ	ρ	A	B	C
\bar{b}	010	180°00'	90°00'	91°12'	180°00'	90°00'
a	100	88 48	90 00	0 00	88 48	90 00
\bar{a}	100	— 91 12	90 00	180 00	91 12	90 00
j	160	— 18 23½	90 00	107 11½	18 23½	90 00
k	120	— 45 20	90 00	134 08	45 20	90 00
l	120	—135 51	90 00	135 21	135 51	90 00
n	160	—161 50½	90 00	109 21½	161 50½	90 00
p	121	—135 51	141 37	116 12½	116 27½	141 37
r	161	— 18 23½	119 46	104 52	34 33	119 46
s	342	—124 41½	134 49	126 16	113 48½	134 49
t	321	—109 40	60 21½	145 31½	107 00½	60 21½

The forms common to all the crystals and those best developed on most of them are: $b\{010\}$, $p\{121\}$, and $t\{321\}$ as shown in Fig. 2. Although these forms can always be seen, it is unusual to find a crystal on which they have not been etched. Many crystals showed the presence of faces in the prism zone, but only one was of sufficient quality to be measured.

EVIDENCE FOR THE PEDIAL CLASS OF PARAHILGARDITE

Since the pyroelectric properties of axinite were described by Haüy (1822), it has stood alone among minerals as an example of triclinic-pedial symmetry. Due probably to the holohedral appearance of axinite, the pedial symmetry has not been accepted by some of the present-day workers. Since parahilgardite is the second mineral to be described as belonging to the pedial class, it seems best to present the evidence on which the determination was made.

The orientation of parahilgardite has been determined by the attached hilgardite; the positive end of $[100]$ of the former joins the negative end of $[100]$ of the latter. This may in part account for the fact that most of the forms listed above are at the back of the crystal and are negative, and that there was little chance for the development of positive faces. On some crystals, however, as on that shown in Figs. 1 and 2, the $a(100)$ face can be seen joining the $b(010)$ face directly with no prism or pyramid present though these faces may exist at the back of the crystal. In Fig. 3,

the right-hand parahilgardite individual shows zones of growth parallel to \bar{a} , b , and either a negative prism or pyramid, but apparently no positive pyramid or prism ever existed. This lack of parallel opposite faces suggests that parahilgardite belongs to the pedial class. The only symmetry element of hilgardite is a reflection plane which is wanting in parahilgardite; a fact that further supports the idea that parahilgardite may be pedial, lacking all symmetry elements.

In order to find more definite evidence of the pedial class, a test to determine whether or not parahilgardite is piezoelectric was made by Prof. G. W. Pierce of Harvard University. By using an apparatus for acoustic research recently described by Noyes and Pierce (1938), he positively determined the presence of piezoelectricity, with a strong electric axis parallel to or nearly parallel to the a crystallographic axis. This fact, taken with the other evidence, proves the absence of a center of symmetry and that parahilgardite is, indeed, pedial. A test was also made on hilgardite which showed a similar electric axis parallel to the a crystallographic axis and, hence, nearly parallel to that of parahilgardite.

PHYSICAL AND OPTICAL PROPERTIES

Parahilgardite has two perfect cleavages parallel to $\{010\}$ and $\{100\}$. The $\{100\}$ cleavage is parallel to the $\{100\}$ cleavage of hilgardite, while the $\{010\}$ cleavage is at an angle of $1^{\circ}12'$ to the $\{010\}$ cleavage of hilgardite. The hardness (5) and specific gravity (2.71) are the same as in hilgardite within the limits of measurement. The optical properties of parahilgardite are as follows:

	Orientation		$n(\text{Na})$	
	φ	ρ		
X	156°	84°	1.630	positive
Y	66	89	1.636	$2V = 35^{\circ}$
Z	0	5	1.664	$r > v$

With the exception of orientation, the above optical properties are the same as those of hilgardite. The only way to distinguish easily between hilgardite and parahilgardite is by observing the extinction angle in the (001) plane (Fig. 4). Z is nearly parallel to c in both minerals. Hilgardite gives parallel extinction, while in parahilgardite the effect is as though the optical indicatrix has been rotated about Z to give an extinction angle of about 20° .

X-RAY MEASUREMENTS

A rotation photograph and Weissenberg photographs of the zero- and first-layer lines were taken with $c[001]$ the rotation axis. The dimensions

of the unit cell calculated from these photographs are given below with those of hilgardite for comparison.

Parahilgardite:	$a_0=11.24\text{\AA}$, $b_0=22.28\text{\AA}$, $c_0=6.20\text{\AA}$
Hilgardite:	$a_0=11.35\text{\AA}$, $b_0=11.12\text{\AA}$, $c_0=6.20\text{\AA}$

From the above it will be seen that the only real difference in the dimensions of the two unit cells is that b_0 of parahilgardite is twice b_0 of hilgardite. The ratio of the cell edges of parahilgardite, $a_0:b_0:c_0=0.5045:1:0.2782$, is that used in the calculation of the angles and elements given in Table 2.

COMPOSITION

A sample of parahilgardite was prepared for analysis by breaking the small crystals from the attached hilgardite. The identity of the physical properties of the two minerals prohibited the separation of uncertain material. Nine-tenths of a gram of parahilgardite was prepared by using a large proportion of the available crystals. The analysis is given in Table 3 with that of hilgardite for comparison.

TABLE 3. ANALYSIS OF PARAHILGARDITE AND CONTENT OF UNIT CELL.

	1	2	3	4	5
B ₂ O ₃	49.18	48.97	50.26	0.7229	B 36.8
CaO	34.41	34.23	35.13	0.6275	Ca 16.0
H ₂ O	6.31	6.07	6.23	0.3462	H ₂ 8.8
Cl	10.37	10.51	10.82	0.3054	Cl 7.8
Insol.	1.89	2.21			
	102.16	101.99			
Less O	2.34	2.37	2.44		
	99.82	99.62	100.00		

1. Analysis of hilgardite by F. A. Gonyer given in Hurlbut and Taylor (1937).
2. Analysis of parahilgardite by F. A. Gonyer.
3. Insolubles deducted and recalculated to 100%.
4. Molecular ratio.
5. Atomic content of unit cell calculated by using the molecular weight of the unit cell, $M_0=2544$.

The two analyses given in Table 3 agree within the limits of error, and the composition for both minerals may be expressed similarly; hilgardite as $\text{Ca}_8\text{B}_{18}\text{O}_{33}\text{Cl}_4 \cdot 4\text{H}_2\text{O}$ and parahilgardite with twice the content of the hilgardite unit cell as $2(\text{Ca}_8\text{B}_{18}\text{O}_{33}\text{Cl}_4 \cdot 4\text{H}_2\text{O})$. A comparison of the chemi-

cal formulae below shows the relation that parahilgardite bears to the other hydrous calcium borates.

Veatchite	$\text{Ca}_2\text{B}_6\text{O}_{11} \cdot 2\text{H}_2\text{O}$
Parahilgardite	$2[\text{Ca}_8(\text{B}_6\text{O}_{11})_3 \cdot \text{Cl}_4 \cdot 4\text{H}_2\text{O}]$
Colemanite	$\text{Ca}_2\text{B}_6\text{O}_{11} \cdot 5\text{H}_2\text{O}$
Meyerhofferite	$\text{Ca}_2\text{B}_6\text{O}_{11} \cdot 7\text{H}_2\text{O}$
Inyoite	$\text{Ca}_2\text{B}_6\text{O}_{11} \cdot 13\text{H}_2\text{O}$

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CRYSTALLOGRAPHY OF TSUMEBITE

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INTRODUCTION

The mineral tsumebite, found only at Tsumeb, Southwest Africa, was described by Busz¹ in 1912 as monoclinic. In the same year Rosický² described similar material from Tsumeb, under the name of preslite, as orthorhombic. Before his paper was published his attention was directed to the article by Busz, just out, and he added a note to his own, suggesting the identity of the two minerals, as the analyses agreed closely, but adhering to his interpretation of the symmetry. There is no doubt of the identity, but the translation from one setting to the other, worked out by him, is wrong.

The Harvard Mineral Collections contain two specimens of tsumebite. On both the mineral forms tiny groups of lustrous emerald-green crystals implanted on smithsonite, as originally described. Crystals of the tsumebite have been measured by the writer, who agrees with Busz in regarding them as monoclinic and as invariably twinned. No untwinned crystals or simple twinned pairs were found on the two specimens, only "groups (of twins) intergrown or tangled with one another" (Busz). In some the crystals are in sub-parallel position, in others "tangled" as in tufts of felt. Few groups are more than 2 mm. across and many are so small that mounting them for measurement is difficult, but all are twinned.

CHARACTER OF THE CRYSTALS

Both previous authors understated the difficulty of measuring the crystal angles, although some faces are smooth and bright and give fairly sharp signals. Much trouble is due to intergrowth of crystals in groups, making it difficult to decide from which one the signals are reflected, as faces on different crystals may be so nearly parallel as to give close double signals. Moreover, on many groups parts of their surfaces that appear under the bench microscope with low power as dull crystal faces prove, when examined on the goniometer with higher magnification, to be irregular or curved splintery areas that reflect no definite signals and cannot be recognized as crystal faces. Scattered about on the groups, in the rough patches and also on edges and corners of faces, are small bright facets which gave good signals. Their distribution on the groups bears no relation to their crystallographic positions and none of them can be

¹ Busz, Karl, Tsumebite, ein neues Blei-Kupfer-Phosphat von Otavi, Deutsch Süd-Wes.-Afrika: *Deutsch. Naturf. u. Ärzte in Münster, Versammlung*, vol. 84, p. 162, 1912.

² Rosický, V., Preslit, ein neues Mineral von Tsumeb in Deutsch Südwestafrika: *Zeits. Krist.*, vol. 51, p. 521, 1912.

identified at sight. When their angular relations are plotted, they are found to occupy the poles of crystal forms known on tsumebite and, as they have been seen and measured repeatedly, there seems to be no reason for not regarding them as valid crystal faces. Their apparently irregular distribution is due to their belonging to different ones of the intergrown crystals.

A uniform setting of such crystals for measurement is necessary as without it the crystals cannot be interpreted. The face called by the writer $\{100\}$ is a narrow face that usually gives a good signal and is flanked on one or both sides by the unit prism, recognizable by its luster and signals. Every group of crystals bears this key combination in one

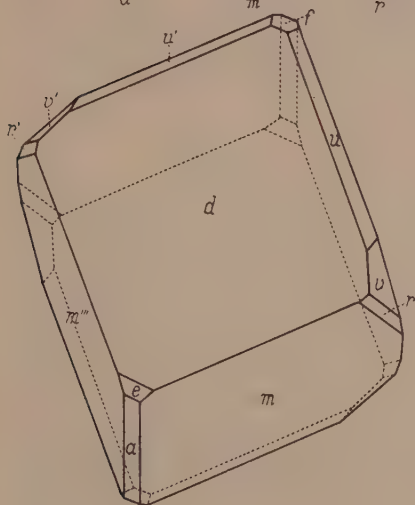
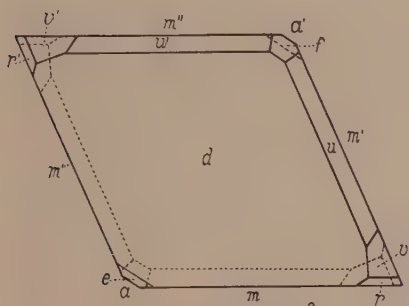


FIG. 1. Plan and clinographic projection of the writer's ideal of an untwinned crystal of tsumebite, showing the commoner forms.

FIG. 2. Clinographic projection of a twinned crystal of tsumebite of the "Y" type, considerably idealized by being drawn as complete.

or more places (Figs. 1 and 2) and each place where it shows is the front coign of a crystal that may be set up on a two-circle goniometer either with the narrow face as the pole or with the combination as the prism one.

This combination includes no terminal faces and so the top of the crystal can not be determined until all the angles have been measured and not even then unless certain needed terminal faces are present and measured.

Some relatively simple groups show the mode of twinning, but not until all the groups had been measured and plotted and their projections carefully analyzed was the true morphology of the crystals discovered. Until then it was not possible to differentiate on a projection the faces belonging respectively to the several crystals of a group or, even though the twin law was known, to distinguish all the twinned face poles from the untwinned ones. The pole of the twinning axis lies at the intersection of four of the zones developed on the crystals and all forms in those zones still lie in the same zones on the projection when twinned (Fig. 3).

Moreover, no one crystal shows faces of all the forms found on tsumebite and most crystals are so intergrown with others that it is impossible by inspection to decide which faces belong to which crystal. The net result of these complexities is an apparently unsymmetrical distribution of face poles on the projections of nearly all the groups measured that is difficult to interpret and to which the former misconceptions of the morphology of the crystals were mainly due, especially as their authors had no sure criteria for distinguishing twinned from untwinned faces or the top of the crystal from the bottom.

METHOD OF ANALYSIS OF THE ANGLE MEASURED

A number of crystal groups detached from the specimens were examined on the goniometer. Some were unsuitable for measurement but all that could be set up in the uniform position were measured and plotted. The measured angles must be plotted on a stereographic projection so that interfacial angles may be compared directly. Such a projection was made of each group measured, as well as a composite projection of all the groups. On those of the more complex groups the face poles are scattered apparently at random and at first sight their interpretation seems hopeless. Some projections defied interpretation and on some the angles were too poor for use, but about 30 had faces that gave usable readings.

All the angles were measured on a two-circle goniometer, so some of them are interfacial and some are interzonal. Several hundred measurements from more than 40 angles were plotted on the projections that

could be used and more than 200 of these measurements were found to be of angles between identifiable faces or zones. They were analyzed for consistency and approximate elements were computed from ten selected interfacial and four interzonal angles. It then became evident that, because of the mode of twinning and the peculiar morphology of the crystals, the elements could be completely determined from the interfacial angle $a-m$ and the interzonal angle $d-a-u$. As there were more and generally better measurements of those two angles than of any others, a final set of elements and angle table were computed from them.

There were twelve forms found on the crystals: the front pinacoid, five prisms, three orthodomes, two clinodomes, and one pyramid. In the position chosen there is no base and no side pinacoid. Of the forms found, seven are common, four are rare but certain, and one is uncertain. All but two were found in both normal and twin positions. The twin law is simple, the twin plane (not an observed form) being either $(\bar{1}22)$ or $(\bar{1}\bar{2}2)$ and trillings were seen twinned on both planes (Figs. 3 and 4). The twin plane passes through opposite faces of the unit prism and nearly coincides with the zone $[\bar{1}12]$. The crystals thus closely simulate isometric forms in their angles, but the face distribution is clearly monoclinic.

TABLE 1. FREQUENCY AND EQUIVALENCE OF FORMS.

Form	Number of Times Identified			Busz	Rosický
	Normal	Twinned	Total		
$a(100)$	35	10	45	$o(\bar{1}01)$	$d(101)$
$k(140)$	3	3	6	.....	.....
$l(120)$	1	2	3	.....	$n(121)?$
$m(110)$	77	23	100	$p(111)$	$p(111)$ in part†
$n(320)$	5	0	5	.....	.....
$o(210)^*$	0	2	2	.....	.....
$d(101)$	16	3	19	$a(100)$	$c(001)$
$e(201)$	3	2	5	.....	$e'(20\bar{1})$
$f(\bar{1}04)$	17	8	25	$d(101)$	.....
$u(011)$	36	31	67	$n(221)$	.....
$v(021)$	4	8	12	.....	.....
$r(241)$	12	12	24	.....	.....

* Uncertain.

† Only four of the eight faces of the unit pyramid of Rosický are equivalent to the unit prism of the writer.

COMPARISON WITH PREVIOUS LISTS

Busz listed only seven forms on tsumebite and Rosický only four on preslite. Therefore, and also because each author has used a different

setting, not all the forms in the three lists can be correlated (Table 1). Comparison of the drawings, however, shows the equivalence of the dominant forms that govern the crystal habit. The forms o , a , d , and p of Busz are easily recognized as equivalent, respectively, to the new forms a , d , f , and m ; and the n of Busz seems to be the new u . The statement of Busz that his zone d - s - n is deeply striated parallel to the zone-axis shows that it must be the zone of oscillatory combination of the writer's f and u (Fig. 5). No forms corresponding to the r and s of Busz have been seen.

Correlation with Rosický's forms is not so easy, as his figures are drawn with three planes of symmetry in the belief that the crystals were orthorhombic. Of the many crystals examined by the writer not one showed a plane of symmetry parallel to the large face, taken as the base by Rosický. He seems not to have distinguished between some faces of his "form" p and the zones of oscillatory combination, which lie nearly, but not actually, in vertical zones with the real faces of his p , which is clearly the same as the new m . Rosický's c , d , and e are the same, respectively, as the new d , a , and f .

The other forms found by the writer were not recorded by the earlier authors; even the pyramid r (241), which is one of the common forms in both normal and twin position, seems to have been overlooked or else taken for a face of some other form.

The setting here adopted seems justified because the zone taken as the prism zone not only includes more forms than any other on the crystals, but is the only one normal to the symmetry plane that will serve satisfactorily as the prism zone. Also the zone taken as the clinodome zone is the only one near the axis of the prism zone. Finally, the new setting gives simple rational indices for the pole of the twinning axis.

The translation from the setting of Busz to the new one is effected by interchanging the front pinacoid and the unit orthodome after reversing the crystal about the (former) vertical axis (Table 1). The transformation of the elements is more complex because both the a and c axes are changed. The upper half of one of Rosický's supposed orthorhombic crystals can be translated to the new setting by rotation on the b axis so that his (101) becomes (100). No such translation of the lower half is possible as the crystals are not orthorhombic and the lower faces of his pyramids are in reality twinned faces of other forms not listed by him. The translation suggested by Rosický from the setting of Busz to his own was based on an erroneous premise and so is not possible.

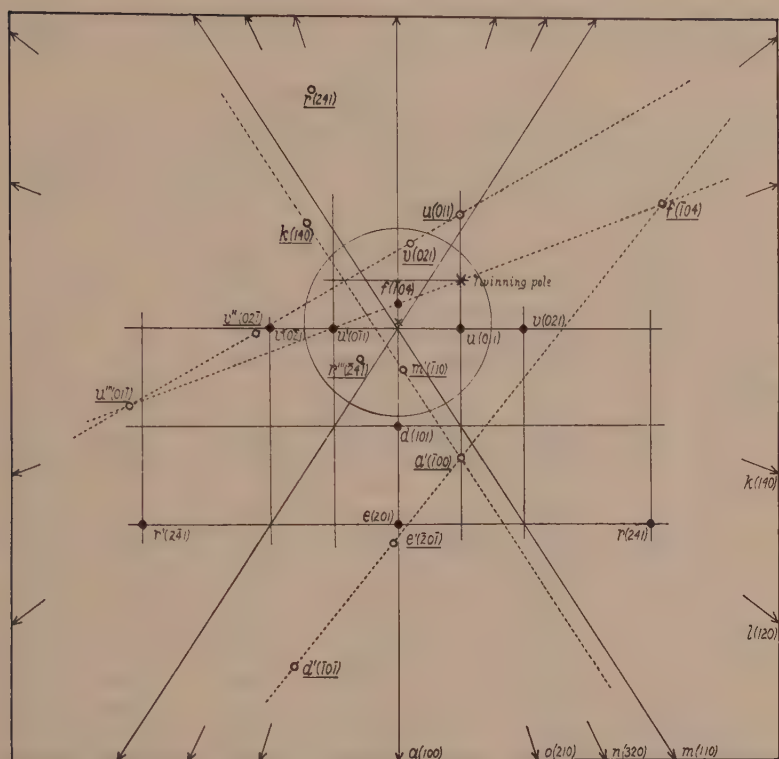


FIG. 3. Gnomonic projection of tsumebite, showing also the poles of the commoner forms in twinned position.

The poles of forms in normal position are shown by full black circles, those of forms in twinned position by open circles. The more important zones in twinned position are shown by dotted lines.

CRYSTAL CONSTANTS

Tsumebite is definitely monoclinic and the elements computed from the new angle measurements to fit the new setting are as follows: $a = 0.65462$, $c = q_0' = 0.67451$, $p_0' = 1.03338$, $e' = 0.07642$, $\mu = 85^\circ 37' 48''$.

The angle table below differs in form from that used at Harvard in that the angles from the several forms to the basal and side pinacoids are omitted, as those forms are not found on the mineral. Instead the angles (M) to the nearest face of the unit prism are given, as that is the most conspicuous and easily recognized form on the crystals and lies in three zones besides the prism zone. As all the crystals are twinned and as there is no way of distinguishing most of the twinned faces except by their angles to others, the commoner forms in twin position are included

in the table. The coordinates of the twinning plane are also given for convenience.

TABLE 2.—ANGLES OF TSUMEBITE

	Form	ϕ	ρ	A	M	x'	y'
In normal position	<i>a</i> 100	90°00'	90°00'	.....	33°08'		
	<i>k</i> 140	20 57	90 00	69 02½	35 54½		
	<i>l</i> 120	37 27	90 00	52 33	19 25		
	<i>m</i> 110	56 52	90 00	33 08	.....	
	<i>n</i> 320	66 29	90 00	23 31	9 37		
	<i>o</i> 210	71 55½	90 00	18 04½	15 03½		
	<i>d</i> 101	90 00	47 58½	42 01½	51 32	1.1098	0.00
	<i>e</i> 201	90 00	64 59	25 01	40 38	2.1432	0.00
	<i>f</i> 104	-90 00	10 18½	79 41½	81 23	-0.1819	0.00
	<i>u</i> 011	6 28	34 10	86 22½	69 01½	0.0764	0.6745
	<i>v</i> 021	3 14½	53 29½	87 23½	61 32	0.0764	1.3490
	<i>r</i> 241	38 27½	73 49	53 19	24 19	2.1432	2.6980
In twinned position	<i>a'</i> 100	64 47	57 43½	40 06	33 08	1.4322	0.6745
	<i>k</i> 140	-131 54	55 02	52 24½	35 54½	-1.0644	-0.9551
	<i>m'</i> 110	82 43	26 34	63 40	66 16	0.4960	0.0634
	<i>u</i> 011	-59 41½	53 12	46 16½	36 54	-1.1539	0.6745
	<i>v</i> 021	-80 12½	40 37	50 05½	53 17½	-0.8452	0.1459
	<i>r</i> 241	-110 17½	69 10	28 46	24 19	-2.4651	-0.9015
	<i>f</i> 104	-24 05	72 14	67 08	36 48½	-1.2734	2.8491
	<i>d'</i> 101	106 50	75 16½	22 13½	21 49½	3.6420	-1.1020
	<i>e'</i> 201	91 19	66 48	23 14	38 38½	2.3329	-0.0536
	<i>u'''</i> 011	162 16	71 41½	73 11½	42 34½	0.9205	-2.8723
	<i>v'''</i> 021	175 38	56 20½	86 54½	59 33	0.1144	-1.4977
	<i>r'''</i> 241	136 15½	28 58	70 26	61 51½	0.3827	-0.3999
Twin- ning plane	I22	-33 08	38 51	69 57	54 57	-0.4403	0.6745

Table 3 gives the final computed values of the angles used for getting the approximate elements, and also of a few other important angles. For comparison, the averages of the measured values of the same angles are listed. There are some rather large differences as well as close agreements but the result is, on the whole, more satisfactory than was expected from the character of the crystals. The elements adopted may not be correct to more than three decimal places, but in order that the

angles in a table shall be mutually consistent, the computations were carried to five decimal places and all angles were computed to seconds.

TABLE 3.—COMPARISON OF ANGLES

Angle	Number of Measurements	Used in Average	Average of Measurements	Computed Values
<i>am</i>	78	33	33°08'	
<i>au</i>	34	23	34 00	
<i>ac=μ</i>	2	2	85°23½'	85°38'
<i>au</i>	16	8	86 15	86 22½
<i>cu</i>	8	8	33 54	33 55½
<i>Ou</i>	5	5	34 15	34 10
<i>ak</i>	1	1	69 00	69 02½
<i>an</i>	5	2	23 30½	23 31
<i>ad</i>	11	6	41 47	42 01
<i>ae</i>	3	2	25 04½	25 01
<i>a'f</i>	11	3	79 27	79 41½
<i>av</i>	3	2	87 28	87 23½
<i>a(a')</i>	7	4	40 41½	40 06
<i>a(f)</i>	3	3	67 20	67 08
<i>a(u''')</i>	4	4	73 08	73 11½
<i>a'(v)</i>	8	2	49 26½	50 05½
<i>cav</i>	2	2	54 17	53 27
<i>ca'(v)</i>	7	4	7 59	8 18
<i>ca(v''')</i>	6	3	56 14	56 16
<i>ca(m')</i>	9	4	3 38	3 37½
<i>ca'(f)</i>	2	2	70 47½	70 39½

Form letters in parentheses indicate forms in twin position.

HABIT AND DETAILED MORPHOLOGY

Both earlier authors describe and draw the crystals as commonly tabular, parallel to a large face. The new measurements show, however, that this "face" is not the same form on all crystals—on some it is {101} poorly developed, on others it is {110} in twinned position, which lies about 4° from the orthodome zone. On still others it is not a single face but is rounded and striated, with irregular facets of {101}, {110} twinned and perhaps of {100} twinned, the whole so rough and dull that only rarely can any good signals be seen.

On untwinned crystals (not yet observed) the dominant form would probably be {101}, and this in combination with the prism {110} would give the crystals a habit roughly resembling a rhombohedron with one pair of opposite faces dominant. Figure 1 shows the writer's mental

picture of an untwinned tsumebite crystal of such a habit, with the back indicated in order better to bring out this resemblance.

The pinacoid a , seen on most crystals, is a narrow or linear, bright and easily recognized face. Of the prisms only m is common or important. Every crystal group bears several large faces of it, but instead of being plane they are usually aggregates of bright facets, slightly divergent and giving confusing multiple signals. The orthodome d is fairly common, but seldom yields a measurable signal, so that measurements have to be made on the brightest reflection. No attempt has been made in the figures to show it as anything but a cleanly developed plane face.

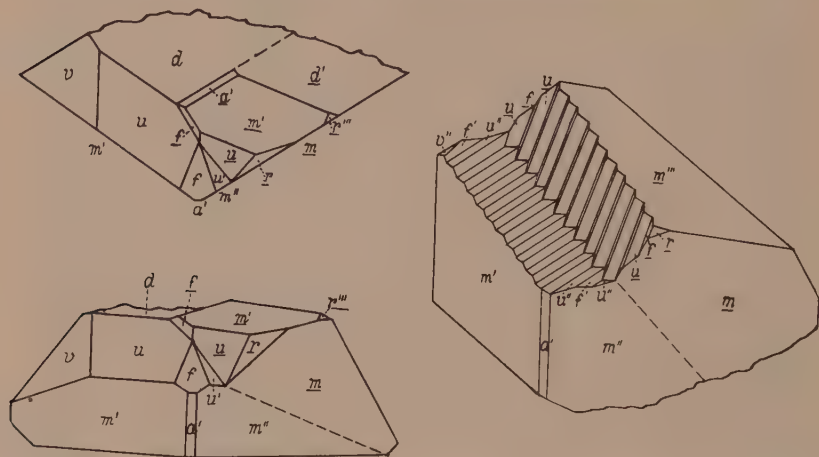


FIG. 4. Plan and clinographic projection of a twinned crystal of tsumebite that furnished the key to the mode of twinning. (Seen from above and from the rear.)

FIG. 5. Clinographic projection of a twinned crystal of tsumebite showing the zones of oscillatory combination, both untwinned and twinned. (Bottom and rear of crystal, inverted by rotation about the b -axis.)

The other domes and the pyramid are as a rule small, plane, brilliant three-, four-, or five-sided facets. The clinodome u , second commonest form, and the orthodome f are found both alone and also together in oscillatory combination in narrow bands that may, if not closely examined, be mistaken for deeply striated faces (Fig. 5). These bands are characteristic of tsumebite crystals and are seen on all well-developed groups. On many they are double, one band being in twin position, and the zigzag suture between them is the trace of the composition face of the twinned crystal. The resultant V-shaped depression across the crystal establishes the orientation as, because of the mode of twinning, it is developed only on the lower side of the twinned crystals.

There are three habits of twinned crystals, differing only in perfection of development of the twinned member—the compact or “V” type, shown in Figs. 4 and 5; the “Y” type (commonest), shown in Fig. 2; and the “X” type, not figured here. Twinning on a pyramid seems to be rare in monoclinic crystals, but Zepharovich has described augite crystals so twinned; on (122), like tsumebite, and in cruciform twins resembling the “X” type of tsumebite twins. (*Jahrb. für Miner.*, etc., 1871, p. 60, Fig. 1.)

All the accompanying crystal figures are more or less idealized, especially those that are completely drawn. This is necessary, as the actual crystals are so intergrown in groups that only parts of them are to be seen, mingled with parts of others. To make “portrait” drawings would be well nigh impossible and they would be so intricate as to be unsatisfactory for portraying the crystals. Every face shown in Fig. 4 could be identified on the crystal but none had the perfection of outline shown in the figure.

COMPOSITION

A number of the crystals, carefully separated from smithsonite and malachite by Dr. Berman, were analyzed by Mr. F. A. Gonyer, chemist of the Department of Mineralogy and Petrography at Harvard University. The result, with those of previous analyses, is given below.

ANALYSES OF TSUMEBITE

	1	2	3	4	5	6
PbO	63.77	65.09	64.71	0.2874	= 4×0.0719	65.84
CuO	11.79	11.97	12.13	0.1524	= 2×0.0762	11.73
P ₂ O ₅	12.01	10.26	10.62	0.0747	= 1×0.0747	10.47
H ₂ O+	12.33	n.d.	12.09	0.6711	= 9×0.0746	11.96
ZnO	—	—	0.54			
CO ₂	—	—	0.24			
Total	99.90	—	99.79	1.1856	= 16×0.0740	100.00

1—Analysis by F. Rössberg and H. Dubigk, 1912.

2—Analysis by J. Frejka, 1912.

3—Analysis by F. A. Gonyer, 1937.

4—Molecular equivalents of 3.

5. Molecular ratio of 3.

6—Composition computed from formula below.

The atomic composition derived from column 5 of the table above is: Pb₄Cu₂P₂H₁₈O₂₀, which can be written in the form: Pb₂Cu(PO₄)(OH)₃ · 3H₂O. Tsumebite is, therefore, a hydrous basic phosphate of lead and

copper. The small amount of Zn and CO_2 found by Gonyer can safely be ascribed to a tiny fragment of smithsonite adhering to one of the tsumebite crystals. Although the three analyses agree rather well they differ just enough so that a different formula may be written for each, but the average of the three, each recomputed to 100 per cent, agrees so closely with Gonyer's analysis as to give the same formula.

ACKNOWLEDGMENTS

The writer wishes to acknowledge his obligation to his colleagues in the Department of Mineralogy at Harvard University—Prof. Charles Palache, by whom he was allowed every facility for the investigation; Dr. Harry Berman, who made the separation of material for analysis, and Mr. F. A. Gonyer, the analyst. Also to Prof. V. Rosický, of the University at Brně, for the loan of a rare copy of the original paper by Busz. Credit is also due to Dr. Berman for having found a crystal in which the method of twinning was clearly seen and from which the twinning law was determined (Fig. 4).

ON POLLUCITE

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1. POLLUCITE AND PETALITE FROM GREENWOOD, MAINE

Introduction. Several years ago in the course of feldspar mining at a quarry at the base of Noyes Mountain in Greenwood, Maine, a mineral supposed to be spodumene was found in quantity and about eight tons of it were taken to the grinding mill at West Paris, Maine. There it lay in a bin for a year or more before it was examined by the late W. D. Nevel of Andover, Maine, who identified the mineral as petalite. He sorted out the petalite and the rejects were sacked and retained until the summer of 1937.

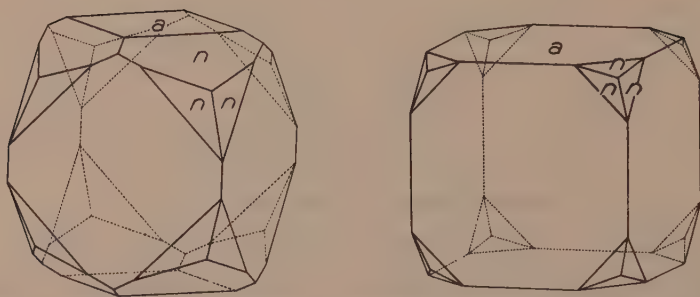
On a visit to the mill that year Richmond selected a quantity of petalite for the Harvard Mineralogical Museum and also carried away some of the waste reject material for examination. This proved, after a delay of months, to contain glassy crystals of pollucite. The effort to secure more of this mineral was unsuccessful, however, since on returning to the mill it was found that the lot had been sent through the grinder.

Occurrence. The specimens studied are clearly replacements of petalite by pollucite and quartz. The pollucite is for the most part massive granular but preserves the laminated structure peculiar to the petalite with which it is associated. Some layers are composed of quartz grains, and elsewhere there are fractures showing indistinct faces of pollucite crystals. In a few cavities in massive pollucite the walls are covered with small crystals of pollucite, the first to be reported from an American locality.

Crystallography. The six crystals measured range in size from two to four millimeters. The forms $a\{100\}$ and $n\{211\}$ are established by the following measurements:

TABLE 1. MEASUREMENT OF ANGLES

Form	No. of Faces	Measured Mean		Calculated	
		ϕ	ρ	ϕ	ρ
$a\ 100$	6	90°02'	90°00'	90°00'	90°00'
$n\begin{Bmatrix} 112 \\ 121 \end{Bmatrix}$	36	44 57	35 12	45 00	35 16
	18	65 59	26 26	65 54	26 34



FIGS. 1a and 1b. Typical crystals of pollucite from Greenwood, Maine, showing the varying development of a 100 and n 211.

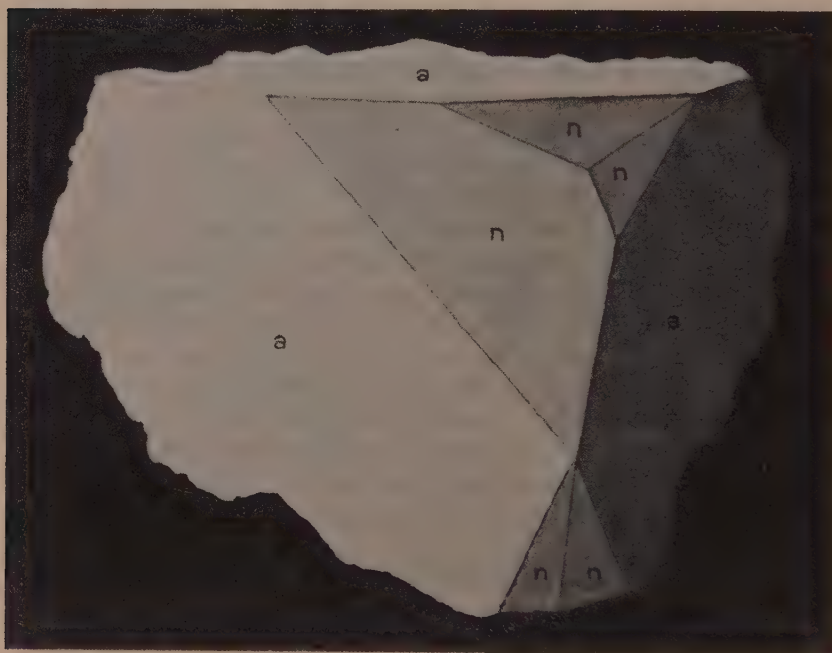


FIG. 2. Drawing of a quartz pseudomorph from the Harvard Mine, Greenwood, Maine. ($\frac{1}{3}$ natural size.)

The two forms are present in varying proportions as shown in the two figures (Figs. 1a and 1b). It is interesting to compare these drawings and Fig. 2 with the reproduction of a quartz pseudomorph described by Landes (1925) in his memoir on the Greenwood ledge near the top of Noyes Mountain. The nature of this pseudomorph is there discussed,

and in a footnote on page 409 it is suggested that it might have been after pollucite. This discovery of crystals with the same habit in so near a locality practically establishes this conclusion. Pollucite in formless glassy masses, often of large size, has been found in various Maine pegmatites. It occurred in the Tamminen pit only a few hundred feet north of the locality here described, as well as in feldspar quarries at Hebron, Buckfield, and Mt. Mica, and in particularly large spherical masses at Newry.

Optical properties. The index of refraction, lower than any previously recorded for pollucite, was determined to be $n(\text{Na}) = 1.507$. This figure, as well as those given for pollucite from other localities, was established by four independent determinations by four observers using two methods, the various readings differing by amounts less than 0.002. Table 2 shows the recorded variations of refractive index in pollucite with decreasing content in Cs_2O . It also shows a corresponding decrease in specific gravity. The figures recorded for the two Greenwood localities were determined by suspension in methylene iodide.

TABLE 2. REFRACTIVE INDEX AND SPECIFIC GRAVITY OF POLLUCITE WITH VARYING CONTENT OF Cs_2O AND H_2O

	Hebron	Greenwood Tamminen	Mt. Mica	Elba	Buck- field	Greenwood Crystals
n	1.526	1.522	1.520	1.520	1.520	1.507
G	2.98	2.97	2.94	2.90	2.90	2.68
% Cs_2O	36.06	35.83		34.30		24.48
% H_2O	1.52	1.62		2.40		3.80

X-ray study of lattice constants. Strunz (1936) determined the lattice parameter of pollucite, $a_0 = 13.71$. Berman (1937) also established a similar constant, $a_0 = 13.66$. The results obtained in our study are as follows:

- A. Massive pollucite, Greenwood. Tamminen Quarry, $a_0 = 13.65$.
- B. Crystals of pollucite, Greenwood. Oxford Mining and Milling Co. Quarry, $a_0 = 13.64$.

Chemistry. The generally accepted formula for pollucite is $\text{Cs}_4\text{Al}_4\text{Si}_9\text{O}_{26} \cdot \text{H}_2\text{O}$. Here sodium in important amounts and smaller amounts of potassium and lithium are included with cesium. Berman (1937) accepted this formula and found the unit cell to contain two molecules. Strunz (1936), on the basis of analyses of pollucite from Rumford, Maine, and from Elba, together with space group criteria, found the unit cell to contain 8 molecules of $\text{Cs}_2\text{Al}_2\text{Si}_4\text{O}_{12} \cdot \text{H}_2\text{O}$.

Dissatisfied with this apparent discrepancy, we prepared two samples of pollucite from the two Greenwood localities and these were analyzed

by Gonyer. His analyses are shown in Tables 3 and 4, and analyses by Wells, together with other analytical data, are contained in Table 5.

TABLE 3. ANALYSIS OF POLLUCITE A, GREENWOOD

	1	2	3		4	5
SiO ₂	44.28	44.21	0.7361	Si	0.7361	33×0.02230
Al ₂ O ₃	16.32	16.29	0.1600	Al	0.3200	15×0.02133
CaO	0.13	0.13	0.0023	Cs+Ca+ }	0.3159	15×0.02160
Cs ₂ O	35.83	35.78	0.1270	K+Na }		
Na ₂ O	1.59	1.59	0.0257	H	0.1800	8×0.02250
K ₂ O	0.38	0.38	0.0041	O	2.2036	100×0.02204
H ₂ O	1.62	1.62	0.0900			
	100.15	100.00				
Cs:Na=4:1						
H ₂ O 4				Cs ₁₅ Al ₁₅ Si ₃₃ O ₉₆ ·4H ₂ O		

1. Analysis of pollucite A by Gonyer.
2. Analysis calculated to 100%.
3. Molecular proportions.
4. Atomic proportions.
5. Number of atoms in the cell formula derived from the x-ray constants.

TABLE 4. ANALYSIS OF POLLUCITE B, GREENWOOD

	1	2	3		4	5
SiO ₂	50.07	49.92	0.8312	Si	0.8312	34×0.02445
Al ₂ O ₃	17.19	17.14	0.1674	Al	0.3348	14×0.02391
CaO	0.09	0.09	0.0016	Cs+Ca+ }	0.3246	14×0.02320
Cs ₂ O	24.54	24.46	0.0868	K+Na+Li }		
Li ₂ O	0.09	0.09	0.0030	H	0.4222	18×0.02346
Na ₂ O	4.34	4.33	0.0700	O	2.5388	105×0.02417
K ₂ O	0.17	0.17	0.0017			
H ₂ O	3.81	3.80	0.2111			
	100.30	100.00				
Cs:Na=1:1						
H ₂ O 9				Cs ₁₄ Al ₁₄ Si ₃₄ O ₉₆ ·9H ₂ O		

Columns 1-5 have the same significance as in the preceding table.

TABLE 5. COMPARISON OF ANALYSES AND THEORETICAL COMPOSITIONS

	1	2	3	4	5	6
SiO ₂	44.21	49.92	43.51	44.37	43.05	49.65
Al ₂ O ₃	16.29	17.14	16.36	16.08	16.61	17.32
Cs ₂ O	35.78	24.46	36.06	34.30	36.76	24.03
Na ₂ O	2.10	4.68	2.55	2.85	2.02	5.08
H ₂ O	1.62	3.80	1.52	2.40	1.56	3.92
	100.00	100.00	100.00	100.00	100.00	100.00
Cs:Na=	4:1	1:1	4:1	3:1	4:1	1:1
H ₂ O	4	9	4	6	4	9

1. Massive pollucite, A.
2. Crystals of pollucite, B.
3. Massive pollucite, Hebron. Analyst, Wells. Recalculated to 100%.
4. Massive pollucite, Elba. Analyst, Wells. Recalculated to 100%.
5. Theoretical composition, Cs₁₆Al₁₆Si₃₂O₉₆·4H₂O.
6. Theoretical composition, Cs₁₄Al₁₄Si₃₄O₉₆·9H₂O.

It is interesting to note that the amount of water is inversely proportional to the content of Cs₂O. The significance of this fact is not apparent.

The formulae given for the massive and crystallized pollucite agree well with the theoretical compositions as given in Columns 5 and 6 of Table 5.

In Berman's silicate classification he includes pollucite in the silica type where 2(Al+Si)=O. The formulae of Tables 3 and 4, which show (Al+Si) equal to 48 atoms, agree with the formula of Strunz and not with that of Berman. But pollucite remains in the silica type.

The above formulae may be generalized to: Cs_{14+x}Al₁₄(Al_xSi)₃₄O₉₆·4-9H₂O, where x may be 0, 1, or 2. For the crystals here described, as well as the material from Elba, the composition is such that $x=0$; when x equals 1, cesium and aluminum are increased and silica decreased 1 atom, giving the formula of material from Noyes Mountain and Hebron; when x equals 2, cesium and aluminum are increased and silica decreased 2 atoms. In the latter case the formula given by Strunz is obtained; his formula may then be considered correct for an ideal pollucite which is not too closely approached in nature.

The writers, therefore, suggest that the generalized formula for pollucite be accepted.

PETALITE

The petalite occurs as cleavage masses with typical laminated structure. The general relations of this mineral in the quarry are unknown;

judging from the available specimens petalite is earlier than albite and lepidolite but appears to be contemporaneous with spodumene.

The exceptional purity of the mineral is noteworthy. Several fragments consist of clear gem material, some of which were used for chemical analysis and optical study.

The optical properties, which appear in the following table, agree with those given by Larsen and Berman (1934):

$X \wedge a = -8^\circ$	$= 1.504$	} +0.003	positive
Y	$= 1.510$		$2V = 84^\circ \pm 2^\circ$
$Z = b$	$= 1.516$		$r > v$, slight

The chemical analysis by Gonyer yields the accepted formula $\text{LiAlSi}_4\text{O}_{10}$. The analysis is given below.

	1	2		3	
SiO_2	78.10	78.44	Si	1.3004	4×0.3251
Al_2O_3	16.64	16.64	Al	0.3264	1×0.3264
Li_2O	5.13	4.92	Li	0.3294	1×0.3294
H_2O	0.22		O	3.2551	10×0.3251

1. Petalite, Greenwood, Maine. Analyst, F. A. Gonyer.
2. Theoretical composition from $\text{LiAlSi}_4\text{O}_{10}$.
3. Atomic proportions and number of atoms.

Acknowledgment. The writers are indebted to Professor Charles Palache for his interest and criticism in the preparation of this paper.

2. POLLUCITE FROM LEOMINSTER, MASSACHUSETTS

Pollucite was first found in Massachusetts in 1937 by Roscoe J. Whitney of Leominster. Through his courtesy specimens sufficient for thorough study reached the Harvard Mineralogical Museum and Richmond was given an opportunity to examine the occurrence.

Occurrence. Spodumene has been reported from Sterling, Massachusetts, for a very long time. It was known, however, only from boulders until Mr. Whitney located a series of ledges of spodumene pegmatite extending into the town of Leominster. At a single point in one of these ledges pollucite has been found in irregular masses up to an inch in diameter. It is associated with green tourmaline, spodumene, amblygonite, cassiterite, columbite, microcline and albite feldspars, quartz, topaz, pyrite and arsenopyrite. Apparently the feldspars and quartz are replaced by spodumene, which in turn is altered to pollucite. Minerals earlier than spodumene have been mechanically deformed, while later minerals show no evidence of disturbance.

Chemistry and Physical Properties. The results of the chemical analysis by F. A. Gonyer are contained in Table 6.

TABLE 6. CHEMICAL ANALYSIS OF POLLUCITE

	1	2	3		4	5
SiO ₂	45.20	45.25	0.7534	Si	0.7534	33×0.02283
Al ₂ O ₃	16.98	17.00	0.1668	Al	0.3336	15×0.02224
Cs ₂ O	33.02	33.06	0.1216	Cs+Na+K	0.3220	15×0.02147
Na ₂ O	2.04	2.04	0.0329			
K ₂ O	0.61	0.61	0.0065	H	0.2266	10×0.02266
H ₂ O	2.04	2.04	0.1133	O	2.2815	101×0.02259
	99.89	100.00				
Cs:Na=3:1				(Cs, Na) ₁₅ Al ₁₅ Si ₃₃ O ₉₆ ·5H ₂ O		
H ₂ O	5					

1. Analysis by F. A. Gonyer.
2. Analysis calculated to 100%.
3. Molecular proportions.
4. Atomic proportions.
5. Number of atoms in the cell formula derived from the cell edge $a_0 = 13.65\text{\AA}$.

The formula derived from the analysis and the cell edge $a_0 = 13.65\text{\AA}$ agrees well with the generalized formula: $\text{Cs}_{14+x}\text{Al}_{14}(\text{Al}_x\text{Si})_{34}\text{O}_{96} \cdot 4-9\text{H}_2\text{O}$.

The specific gravity 2.89 was determined by suspension; the index of refraction $n(\text{Na}) = 1.520$.

If we tabulate the characters of the new pollucite as is done in Table 2 on a preceding page for other occurrences, we have:

	Leominster
n	1.520
G	2.89
%Cs ₂ O	33.06
%H ₂ O	2.04

The figures bring it very close to the Elba pollucite with a slightly lower water content.

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CANNIZZARITE AND BISMUTHINITE FROM VULCANO

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Cannizzarite was described from the deeper parts of fumaroles on Vulcano, Lipari Islands, by Zambonini, De Fiore, and Carobbi (1925), who pointed out the similarity between their chemical formula for the new mineral ($\text{Pb Bi}_4 \text{S}_7$) and that of livingstonite ($\text{Hg Sb}_4 \text{S}_7$). A prominent prism at about 45° to (010) suggested a similarity between cannizzarite and stibnite, which is pseudo-tetragonal and very like bismuthinite in form. Since livingstonite was early described as resembling stibnite in form, a relation between cannizzarite, livingstonite, stibnite, and bismuthinite seemed to be established. Recently, however, Richmond (1936) has shown that livingstonite is monoclinic and quite unrelated to stibnite. Furthermore, the pseudo-tetragonal prism noted on cannizzarite appears actually to have been measured on bismuthinite. Consequently, the suggested relations of cannizzarite are without foundation.

In his study of the structure of bismuthinite, Hofmann (1933) used crystals from Vulcano supplied by Professor F. Bernauer, who had found cannizzarite to be a mixture of bismuthinite and a platy, metallic mineral, which he did not investigate further. Hintze (1936, p. 105), therefore, doubts the validity of the species.

CANNIZZARITE

Material. The specimens described as cannizzarite in the Harvard Mineralogical Museum were supplied by R. Palumbo of Naples. They are of two types, both from Vulcano. One sample consists of a bottle of loose, acicular crystals, 1 cm. or more in length, deeply striated and, in a few cases, well terminated. These prove to be bismuthinite, which will be described later. The other specimen consists of minute, prismatic crystals attached to a mass of dense, gray, perlitic andesite. Many of the crystals show an iridescent tarnish; others have a splendid, metallic luster. Measurement of the terminal planes proved difficult because of the minute size of the faces and the resulting poor reflections; the results show, however, that cannizzarite, although orthorhombic, is not homeomorphous with the stibnite group.

Morphology. The crystals are minute, flattened, orthorhombic prisms, plates, or laths less than $1.0 \times 0.3 \times 0.1$ mm. in size. The axis of elongation is taken as $c[001]$; the plane on which all of the crystals are more or less flattened becomes $a(100)$. The main zone is rarely free from vertical striations which give trains of weak reflections, only a few of which were observed repeatedly on several crystals. Of the many forms noted on the twenty-four measured crystals only those observed repeatedly in

good position are considered as certain; forms observed but once in good position are retained subject to confirmation; the remaining forms, mostly in the striated zone, are uncertain.

In the adopted notation, which gives geometrical elements corresponding to the structural cell, the certain forms, in order of decreasing importance, are:

$a\{100\}$, $m\{110\}$, $w\{011\}$, $Q\{210\}$, $y\{810\}$, $d\{201\}$, $p\{111\}$, $G\{211\}$, $h\{140\}$, $S\{410\}$, $x\{031\}$.

The forms requiring confirmation are:

$c\{001\}$, $b\{010\}$, $o\{190\}$, $i\{130\}$, $j\{120\}$, $k\{230\}$, $I\{560\}$, $O\{430\}$, $N\{750\}$, $P\{320\}$, $R\{310\}$, $T\{920\}$, $U\{510\}$, $V\{11.2.0\}$, $W\{610\}$, $Y\{15.2.0\}$, $Z\{16.1.0\}$, $e\{232\}$, $f\{121\}$, $g\{311\}$.

The uncertain forms, for which letters are unnecessary, are:

$\{1.12.0\}$, $\{1.10.0\}$, $\{2.13.0\}$, $\{160\}$, $\{150\}$, $\{250\}$, $\{670\}$, $\{760\}$, $\{650\}$, $\{540\}$, $\{530\}$, $\{740\}$, $\{021\}$, $\{052\}$, $\{403\}$, $\{133\}$, $\{182\}$, $\{263\}$, $\{544\}$, $\{361\}$.

The best mean measured angles: $(100):(110)=38^\circ50'$; $(001):(011)=15^\circ47\frac{1}{2}'$ give the geometrical elements: $a:b:c=0.8050:1:0.2828$.

TABLE 1. CANNIZZARITE: MEASURED AND CALCULATED ANGLES

Form	No. xls.	No. times	Measured Range		Weighted Mean Calculated			
			ϕ	ρ	ϕ	ρ	ϕ	ρ
100	24	48	90°00'–	90°00'–	90°00'	90°00'	90°00'	90°00'
140	5	5	15 58 –18°00'	90 00 –	17 06	90 00	17 15	90 00
110	15	22	47 40 –54 14	90 00 –	51 10	90 00	51 10	90 00
210	6	7	66 32 –70 00	90 00 –	68 15	90 00	68 04½	90 00
410	7	8	78 56 –77 37	90 00 –	78 23	90 00	78 37½	90 00
810	9	9	84 05 –84 55	90 00 –	84 14	90 00	84 15	90 00
011	10	17	0 00 –	15 16 –16°40'	0 00	15 47½	0 00	15 47½
031	4	5	0 00 –	39 30 –40 34	0 00	40 21	0 00	40 18½
201	5	7	90 00 –	33 19 –36 42	90 00	35 00	90 00	35 05½
111	4	7	48 56 –54 38	23 02 –25 42	51 05	24 13	51 10	24 16½
211	6	7	67 24 –72 36	35 38 –38 19	68 43	37 47	68 04½	37 08½

Due to the imperfection of the crystals the measured angles in Table 1 agree only moderately well with the calculated values.

Table 2 gives a formal angle table for the certain forms. Figure 1 represents a typical crystal flattened on $a\{100\}$.

X-ray measurements. The following x-ray photographs were taken of

TABLE 2. CANNIZZARITE: ANGLE TABLE

Cannizzarite— $\text{Pb}_3\text{Bi}_6\text{S}_{11}$						
Orthorhombic; dipyrarnidal: $2/m \ 2/m \ 2/m$						
$a:b:c=0.8050:1:0.2828$; $p_0:q_0:r_0=0.3513:0.2828:1$						
$q_1:r_1:p_1=0.8050:2.8463:1$; $r_2:p_2:q_2=3.5359:1.2423:1$						
Forms	ϕ	ρ	ϕ_1	ρ_1	ϕ_2	ρ_2
a 100	90°00'	90°00'	—	0°00'	0°00'	90°00'
h 140	17 15	90 00	90°00'	72 45	0 00	17 15
m 110	51 10	90 00	90 00	38 50	0 00	51 10
Q 210	68 04½	90 00	90 00	21 55½	0 00	68 04½
S 410	78 37½	90 00	90 00	11 22½	0 00	78 37½
y 810	84 15	90 00	90 00	5 45	0 00	84 15
w 011	0 00	15 47½	15 47½	90 00	90 00	74 12½
x 031	0 00	40 18½	40 18½	90 00	90 00	49 41½
d 201	90 00	35 05½	0 00	54 54½	54 54½	90 00
p 111	51 10	24 16½	15 47½	71 19½	70 38½	75 03½
G 211	68 04½	37 08½	15 47½	55 56½	54 54½	76 58½

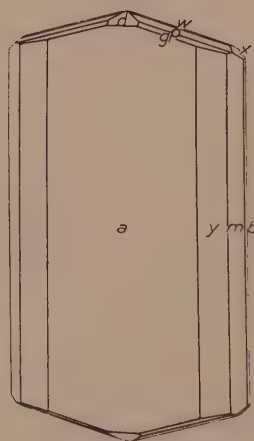


FIG. 1. Cannizzarite from Vulcano.

cannizzarite, using copper radiation: Laue, normal to (100); rotation about [001]; zero- and first-layer Weissenberg about [001]; and zero-layer Weissenberg about [010]. The photographs gave an orthorhombic lattice with the cell edges:

$$a_0 = 11.73\text{\AA}, b_0 = 14.47\text{\AA}, c_0 = 4.076\text{\AA}$$

$$a_0:b_0:c_0 = 0.8106:1:0.2817$$

These results are in good agreement with the morphological ratio:

$$a:b:c = 0.8050:1:0.2828$$

Combining the cell volume with the measured specific gravity, 4.8, we obtain the molecular weight of the unit cell:

$$M_0 = 2012$$

The following reflections were present on the Weissenberg photographs:

$$\begin{aligned}(hkl) & \text{—all orders} \\ (hk0) & \text{—all orders} \\ (0kl) & \text{—}k+l, \text{ even} \\ (h0l) & \text{—}h, \text{ even}\end{aligned}$$

Since the same forms were observed on both ends of doubly terminated crystals, the symmetry is holohedral. This, together with the above space group criteria, establishes the space group as $D_{2h}^{16}\text{--}Pnam$.

Morphological development is in agreement with the space group requirements, according to the Donnay rule (1937). According to these requirements, systematic omissions occur only in the $\{0kl\}$ and $\{h0l\}$ forms. $\{011\}$, $\{031\}$, and $\{201\}$ are the only certain forms in these categories which are listed in the angle table, and the indices of these forms conform to the criteria for the space group.

Physical properties. Cannizzarite has a good cleavage parallel to $\{110\}$. The hardness is probably between 2 and 3. The luster is metallic on untarnished surfaces. The specific gravity, 4.8, was obtained with the micro-pyknometer; the value calculated from the cell volume and theoretical composition is 4.82. A sample of bismuthinite accompanying the cannizzarite gave the specific gravity 6.46. Zambonini gave the value 6.54 for cannizzarite which was evidently measured on material consisting largely of bismuthinite.

Composition. On a carefully separated sample of cannizzarite F. A. Gonyer obtained the values given in column 1 of Table 3.

The new analysis gives the cell formula $Pb_3Bi_5S_{11}$ and compares well with the percentage weights calculated for this composition. Carobbi's analysis differs widely from the newly found composition, due no doubt to admixture with bismuthinite.

TABLE 3. ANALYSES OF CANNIZZARITE AND BISMUTOPLAGIONITE

	1	2	3	4	5
Pb	31.33	3.05	15.79	33.02	30.79
Bi	51.25	4.90	66.00	46.83	51.75
		5.00			
Fe	0.27	0.10	0.51	...	...
Cu	0.00	—	trace	...	...
As	0.00	—	—	...	...
Sb	0.19	0.04	—	3.05	...
		10.79			
S	17.16	10.75	17.70	17.10	17.46
	100.20		100.00	100.00	100.00

1. Cannizzarite, Vulcano, Lipari Islands; analyst F. A. Gonyer.
2. Number of atoms in the unit cell ($M_0=2012$).
3. Cannizzarite, Vulcano, Lipari Islands; analyst Carobbi, in Zambonini, De Fiore and Carobbi (1925).
4. Bismutoplagonite, Montana; analyst Shannon (1920). Reduced to 100 per cent after deducting 18.8 per cent insoluble and 1.25 per cent FeS.
5. Theoretical values for formula $Pb_5Bi_8S_{11}$.

IDENTITY OF CANNIZZARITE AND BISMUTOPLAGIONITE

Shannon (1920) described a new mineral from Montana, having the composition $Pb_5Bi_8S_{17}$, for which he proposed the name bismutoplagonite, indicating a relation to plagonite with the composition $Pb_5Sb_8S_{17}$. Since the proportions as indicated in Shannon's formula $Pb_5Bi_8S_{17}$ are close to those found for cannizzarite $Pb_3Bi_5S_{11}$, as shown; also as the similarity between Shannon's analysis (column 4, Table 3) and the new analysis of cannizzarite is rather striking, further observations were made on the type bismutoplagonite.

The crystals are minute and very imperfect. Five very poor crystals were finally measured on the goniometer, and only one of these gave fair reflections from the terminal planes. The crystals proved to be orthorhombic, as suggested by Shannon, with approximate polar elements close to those of cannizzarite:

Bismutoplagonite: $p_0:q_0:r_0=0.342:0.267:1$

Cannizzarite: $p_0:q_0:r_0=0.351:0.282:1$

A rotation photograph about [001] gave a lattice period identical with the corresponding period in cannizzarite. A zero-layer Weissenberg photograph about [001] did not give closely comparable values for the reciprocal lattice periods.

Bismutoplagonite: $a^*=0.115$; $b^*=0.100$ (Cu)

Cannizzarite: $a^*=0.132$; $b^*=0.105$ (Cu)

The discrepancy in a^* may be due to the fact that the crystal used was, in reality, a sub-parallel aggregate.

The physical properties of bismutoplagonite, as given by Shannon, agree with those of cannizzarite, except for the specific gravity, for which Shannon obtained 5.35 as against 4.8 found for cannizzarite. A second test on Shannon's material is impossible with the limited material available.

Bismutoplagonite and cannizzarite, thus, have essentially identical properties. Although the name bismutoplagonite has priority, it seems unwise to retain it since the implied relation to plagonite is not well founded. It seems better to adopt the name cannizzarite for the species in spite of the fact that the original description was made on a mixture of two minerals.

BISMUTHINITE

Two samples from Vulcano were studied, both labeled cannizzarite. Both proved to be bismuthinite; and it is probable that all bottled

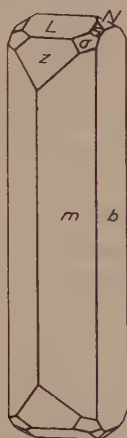


FIG. 2. Bismuthinite from Vulcano.

samples of cannizzarite are, likewise, bismuthinite. The second lot of material, purchased for this study, consists of well terminated crystals, giving good measurements which permitted exact determination of the elements. Many of the crystals are hollow prisms on which almost every face consists of two parts giving coincident reflections. In some cases the termination is unbroken, and excellent reflections are obtained.

The proper setting of bismuthinite corresponds to the structural lattice determined by Hofmann (1933). This setting is related to the classical setting, used by Dana (1892), by the transformation:

$$\text{Dana to Hofmann: } 300/030/001$$

In the new setting, the propriety of which was recognized by Peacock (1933) and Ungemach (1934), the principal forms observed on the Vulcano bismuthinite are, in order of decreasing importance:

$$b\{010\}, m\{110\}, z\{301\}, \sigma\{211\}, s\{111\}, L\{101\}.$$

These determine the common habit illustrated in Fig. 2. The following known forms were, also noted:

$$t\{150\}, q\{130\}, x\{250\}, o\{120\}, d\{230\}, g\{450\}, \\ n\{210\}, h\{310\}, f\{410\}, N\{021\}, u\{221\}, \lambda\{311\}.$$

In addition to these, the following new forms were observed. All except $w\{121\}$, noted four times, require confirmation. The majority of the new forms are based on single reflections from the trains of signals given by the striated vertical zone.

$$\{180\}, \{3.10.0\}, \{370\}, \{470\}, \{10.7.0\}, \{730\}, \{20.7.0\}, \{610\}, \\ \{10.1.0\}, \{12.1.0\}, \{023\}, \{504\}, \{904\}, \{502\}, \{601\}, \{377\}, \\ w\{121\}, \{955\}, \{16.3.6\}, \{12.1.2\}, \{631\}.$$

TABLE 4. BISMUTHINITE: MEASURED AND CALCULATED ANGLES

Form	No. xls.	No. times	Measured Range		Weighted Mean		Calculated	
			ϕ	ρ	ϕ	ρ	ϕ	ρ
121	4	4	27°08'–27°17'	38°02'–39°05'	27°10'	38°20'	26°53'	38°06½'

In Table 4 the measured angles are compared with those calculated from Peacock's elements on bismuthinite from Tasna, Bolivia, transformed to the new setting by dividing the c -axis by three:

$$a:b:c=0.9862:1:0.3498$$

A determination of elements for the Vulcano bismuthinite, in the old setting, gave values closely similar to those recently obtained by Bianci

(1924), Peacock (1933), and Carpanese (1936). The variations are probably due to slight variations in composition.

TABLE 5. BISMUTHINITE: COMPARISON OF ELEMENTS

	$a:b:c$	(010):(110)	(001):(101)	
Crodo	0.9844:1:1.0447	45°27'	46°42'	Bianci
Tasna	0.9862:1:1.0493	45 24	46 46½	Peacock
Artificial	0.9879:1:1.0660	45 21	47 11	Carpanese
Vulcano	0.9820:1:1.0548	45 31½	47 03	Wolfe

A measurement of the specific gravity gave 6.46, which is normal for the species but lower than the value 6.81 calculated from structural data.

An analysis gave the composition listed below:

TABLE 6. BISMUTHINITE ANALYSIS

	1	2
Bi	80.29	81.3
Fe	0.38	...
Pb	0.00	...
Sb	0.00	...
As	0.00	...
S	19.48	18.7
	100.15	100.0

1. Bismuthinite, Vulcano, Lipari Islands; anal. F. A. Gonyer.
2. Theoretical values for Bi_2S_3 .

The Vulcano bismuthinite is, therefore, an unusually pure occurrence; the slight deficiency in bismuth might account for the discrepancy in specific gravity.

The author wishes to acknowledge the assistance he has received from Professor Palache, who provided the material for this study, Mr. Richmond, who took the x-ray photographs and aided in their interpretation, Dr. Berman, who advised on various problems, Mr. Gonyer, who made the analyses, Dr. Foshag of the National Museum, who kindly loaned some of Shannon's type bismutoplagonite, and Dr. Peacock, who helped to prepare this paper.

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CRYSTALLOGRAPHY OF LANARKITE

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Lanarkite, Pb_2SO_5 , has been found in measurable monoclinic crystals only from the Susanna Mine, Leadhills, Lanarkshire, Scotland (Heddle, 1901). The only complete description of these crystals was given by Schrauf (1877), who chose pseudorectangular axes ($\beta = 91^\circ 49'$). Goldschmidt chose a setting with the axes considerably inclined ($\beta = 119^\circ 23'$). Specimens in the Harvard collection from the type locality were examined by Richmond in connection with other work; these proved to be a rich source of new data. X-ray investigation revealed that neither the Schrauf nor the Goldschmidt settings were in agreement with that of the simplest structural cell.

X-Ray Determinations. A carefully selected crystal, approximately 0.5 millimeter long, was employed for rotation and Weissenberg photographs. The results of measurements and calculations of the photographs gave the following cell edge lengths for the base-centered lattice which was chosen: $a_0 = 13.73\text{\AA}$, $b_0 = 5.68\text{\AA}$, $c_0 = 7.07\text{\AA}$; $a_0:b_0:c_0 = 2.417:1:1.245$, $\beta = 116^\circ 13'$.

The choice of the correct axial directions in this case, except for the b -axis, which is fixed by symmetry considerations, is not without ambiguity. If, in the reciprocal lattice, the three shortest translations, with c^* greater than a^* , are chosen, giving the cell with the least axial obliquity, the following reflections are observed on the Weissenberg pictures:

- (hkl) —with $h+k+l$, even
- $(h0l)$ —with $h+k$, even
- $(0k0)$ —with k , even

The criterion, (hkl) with $h+k+l$, even, indicates a body-centered or "I" lattice. As there are, conventionally, only two types of monoclinic lattices, the primitive and the face-centered, it is advisable to choose a cell which may be referred to one of these lattice types.

A face-centered lattice may be obtained if the next shortest translation is taken for c^* , with a^* and b^* remaining identical with the a^* and b^* of the body-centered cell. The reflections appearing from this lattice are:

- (hkl) —with $h+k$, even
- $(h0l)$ —with h , even
- $(0k0)$ —with k , even

The criterion (hkl) with $h+k$, even, is that for the base-centered or "C" lattice, which is adopted for the mineral. The space group, fixed by the above criteria plus the fact that a morphological investigation showed

no hint of hemihedry, becomes $C_{2h}^3-C 2/m$. The transformations from the base-centered lattice to the body-centered lattice and vice versa are, respectively: $101/010/001$ and $10\bar{1}/010/001$.

The relation of the "C" lattice to the "I," Schrauf, and Goldschmidt cells is given in Fig. 1.

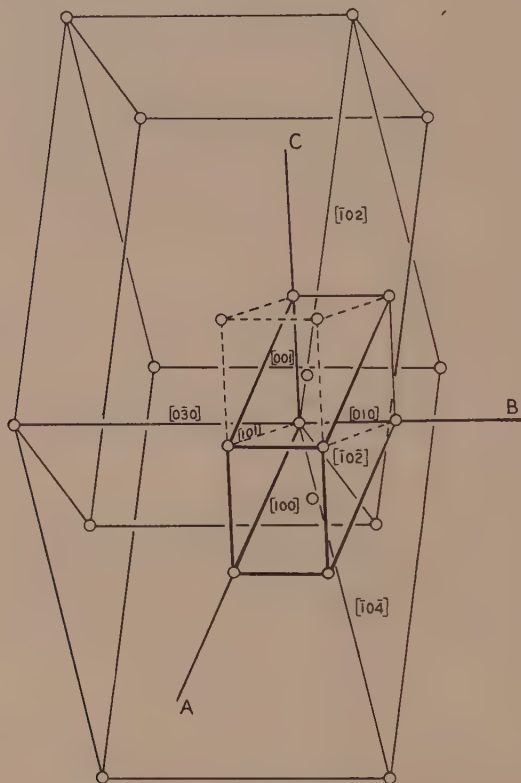


FIG. 1. Lanarkite. Structural lattice showing the chosen base-centered "C" cell with edges $[100]$, $[010]$, $[001]$; the body-centered "I" cell with edges $[101]$, $[010]$, $[001]$; Schrauf's cell with edges $[102]$, $[030]$, $[102]$; and Goldschmidt's cell with edges $[104]$, $[030]$, $[102]$. The volume of Schrauf's cell is 12 times, and that of Goldschmidt is 18 times that of the structural cell.

Morphology. As the structural study had disclosed that the old settings were incorrect, a further morphological study of the material in hand seemed advisable. Eleven well-developed crystals, varying in length from 1 mm. to 5 mm., were measured. On the basis of these measurements, new elements for the base-centered setting were calculated. A comparison between these elements and those of Schrauf, transformed

to the base-centered setting, with those obtained by x -ray analysis is given below.

	$a:b:c$	β
Richmond and Wolfe	2.4137:1:1.2363	116°06'
Schrauf	2.4149:1:1.2424	115 48
X -ray	2.417 :1:1.245	116 13

There is essential agreement between the various elements, although Schrauf's value for β departs from the x -ray value by 0°25'. Because of this agreement, Schrauf's values are retained.

Schrauf's elements may be transformed to the base-centered setting by the method of Wolfe (1937), using the transformation formula, $\frac{2}{3}0\frac{2}{3}/0\frac{2}{3}0/\frac{1}{4}0\frac{1}{4}$. Similarly, Goldschmidt's elements, derived from Schrauf's work, may be transformed to the base-centered setting by the formula, $\frac{2}{3}0\frac{2}{3}/0\frac{2}{3}0/\frac{1}{6}0\frac{1}{6}$. The reverse transformations are, respectively: $\bar{1}0\bar{2}/0\bar{3}0/102$ and $\bar{1}0\bar{4}/0\bar{3}0/\bar{1}02$. The meaning of these transformations in the space-lattice is readily observed in Fig. 1.

Five new, well-authenticated forms were observed. In the discussion which follows, the indices refer to the "C" lattice. The new forms are: $c\{001\}$, $d\{103\}$, $E\{\bar{4}03\}$, $R\{\bar{8}01\}$, and $P\{\bar{1}11\}$. All were seen at least twice in good position and, except for $d\{103\}$, were sufficiently prominent to be figured (Fig. 2). In addition, the forms $m\{110\}$, $f\{201\}$ (with indistinct cleavage), $F\{\bar{2}01\}$ (with perfect cleavage), and $U\{\bar{4}01\}$ (with indistinct cleavage), first observed by Schrauf, were each observed several times in this study.

Five other forms— $\{100\}$, $\{101\}$, $\{\bar{1}01\}$, $\{401\}$, and $\{601\}$ —were each observed twice, but the reflections were of poor quality. These forms, therefore, require confirmation. $\sigma\{205\}$ and $s\{9.10.3\}$, observed by Schrauf, were not seen by the authors.



FIG. 2. Lanarkite—Typical crystals from Leadhills, Scotland.

A tabulated comparison of the measured and calculated values for the new, certain forms is given in Table 1. As the crystals are always elongated parallel to the b -axis, measurement of the crystals was made with this axis vertical. The ϕ and ρ angles obtained in this orientation correspond to ϕ_2 and ρ_2 of the angle table, and direct comparison may thus be made.

TABLE 1. LANARKITE: MEASURED AND CALCULATED ANGLES

Form	No. xls.	No. times	Measured Range		Weighted Mean		Calculated	
			ϕ_2	ρ_2	ϕ_2	ρ_2	ϕ_2	ρ_2
001	3	3	63°47'– 64°23' 90°00'–		64°07'	90°00'	64°12'	90°00'
103	2	2	55 50 55 55 90 00		55 53	90 00	56 01½	90 00
403	2	2	105 13 105 20 90 00		105 18	90 00	105 34	90 00
801	7	11	164 38 166 05 90 00		165 15	90 00	166 15	90 00
I11	5	9	94 03 95 19 38 58 –39°07'		95 04	39 03	95 03	38 56½

The indices for all of the forms noted in the literature in the base-centered, Schrauf, and Goldschmidt settings are given below. The new forms are marked with an asterisk.

Base-centered		Schrauf	Goldschmidt
<i>c</i>	001*	I01	201
<i>m</i>	110	<i>z</i> 131	<i>z</i> 131
<i>d</i>	103*	705	13.0.5
σ	205	σ 302	σ II.0.4
<i>E</i>	403*	I05	405
<i>f</i>	201	<i>a</i> 100	<i>a</i> 100
<i>F</i>	201	<i>c</i> 001	<i>c</i> I02
<i>U</i>	401	<i>u</i> 103	<i>u</i> 001
<i>R</i>	801*	305	205
<i>P</i>	I11*	I33	I11
Unconfirmed			
	100*	101	101
	101*	301	501
	I01*	I03	I01
	401*	301	401
	601*	201	502
	9.10.3	<i>s</i> 1.10.5	<i>s</i> I.10.5
Discarded			
	234.4.57	<i>v</i> 10.1.29	1.2.58
	75.4.18	<i>w</i> 13.4.37	1.4.37
	24.2.57	<i>\tau</i> 23.1.15	42.1.15

Vicinal forms similar to the last three listed above were observed on the larger crystals. In all cases they were too dull for accurate measurement, and are apparently solution forms. The faces on the smaller crystals, however, gave clear, bright reflections with rational indices. It seems advisable to discard the vicinal forms from the form list.

An angle table, summarizing the crystallographic elements and angles, is given below.

TABLE 2. LANARKITE: ANGLE TABLE

Lanarkite— Pb_2SO_5							
Monoclinic; prismatic— $2/m$							
$a:b:c=2.4149:1:1.2424$; $\beta=115^\circ 48'$; $p_0:q_0:r_0=0.5145:1.1186:1$							
$r_2:p_2:q_2=0.8940:0.4600:1$; $\mu=64^\circ 12'$; $p_0'=0.5714$, $q_0'=1.2424$, $x_0'=0.4834$							
Forms	ϕ	ρ	ϕ_1	$\rho_1=A$	ϕ_2	$\rho_2=B$	Dana '92
<i>c</i> 001	90°00'	25°48'	64°12'	90°00'	0°00'	64°12'	
<i>m</i> 110	24 42	90 00	0 00	24 42	79 33	65 18	<i>z</i>
<i>d</i> 103	90 00	33 58½	56 01½	90 00	8 10½	56 01½	
σ 205	90 00	35 27	54 33	90 00	9 39	54 33	σ
<i>E</i> 403	−90 00	15 34	105 34	90 00	41 22	105 34	
<i>f</i> 201	90 00	58 24½	31 35½	90 00	32 36½	31 35½	<i>a</i>
<i>F</i> 201	−90 00	33 24	123 24	90 00	59 12	123 24	<i>c</i>
<i>U</i> 401	−90 00	60 58½	150 58½	90 00	86 46½	150 58½	<i>u</i>
<i>R</i> 801	−90 00	76 15	166 15	90 00	102 03	166 15	
<i>P</i> 111	− 4 03	51 14½	95 03	38 56½	57 20	93 09½	

Unconfirmed:—{100}, {101}, {101}, {401}, {601}, {9.10.3}

Discarded:—{6.2.57}, {234.4.57}, {75.4.18}

OPTICS

The refractive indices and optical orientation were determined by the immersion method, giving the following results:

	$n(\text{Na})$	
X	1.928	} ± 0.003 negative $2V=60^\circ \pm 2^\circ$
Y= <i>b</i>	2.007	
Z \wedge c=30°	2.036	

CHEMISTRY

Using an existing analysis by E. Pisani (1873) and a density 6.92, determined here by the float method, together with the cell volume, $V_0=494.4$, the contents of the unit cell were determined and are given in the following table:

TABLE 3. LANARKITE: ATOMIC CONTENT OF UNIT CELL

	1		2	3	4
PbO	84.63	Pb	0.379	7.86	8
SO ₃	15.37	S	.191	3.96	4
		O	.952	19.74	20

1. Lanarkite, Leadhills, Scotland. Analysis reduced to 100%. Analyst, E. Pisani (1873).
2. Atomic proportions.
3. Number of atoms in unit cell yielding the formula $\text{Pb}_8\text{S}_4\text{O}_{20}$.
4. Theoretical number of atoms in unit cell for $M_0=2073.8$.

ACKNOWLEDGMENTS

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A NEW MICROPYCNOMETER FOR THE DETERMINATION OF DENSITIES OF HEAVY SOLIDS

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ABSTRACT

A constant volume quartz-glass pycnometer is described which has been found experimentally capable of giving results with a probable error of about 1.0%, using .03 to .04 cc. of material with a specific gravity of 4.0 to 7.5, and weighing on an ordinary chemical balance accurate to 0.0001 gram.

INTRODUCTION

Various micropycnometric methods have been described in the literature (Bannister, 1938; Syromyatnikov, 1935; Hauptmann, 1934; Retgers, 1899). The present method utilized a pycnometer about the size of that used by Retgers (1899), who employed benzol as the displacement fluid and closed his pycnometer by means of a glass plate covering the opening. Wulff and Heigl (1931) have used toluene as the displacement fluid. Syromyatnikov (1935) described a micropycnometer similar to that of Retgers. Bannister (1938) analyzed the systematic errors of the pycnometric method and concluded that Syromyatnikov's method is not as accurate as claimed because the error, due to temperature uncertainty, is probably large. While temperature errors are often serious in larger pycnometers, in the micropycnometer of this type they are small compared with certain other errors, as will be shown later.

One of the difficulties in the application of methods like that of Bannister (1938) is the requirement that weighings be made on a microbalance. Such an instrument is not often easily available. Bannister used a centrifuge to wet the sample and to remove air bubbles. This method does not seem to give as consistent results with the pycnometer here described as the method of boiling under reduced pressure.

MICROPYCNOMETER

Figure 1 is a vertical section of a small-volume quartz-glass pycnometer made for the writer by the Macalaster Bicknell Company of Cambridge, Mass. The volume of the instrument is 0.1319 cc., as measured with the liquid meniscus opposite a scratch on the capillary tube; this scratch should, of course, completely circle the tube to allow the elimination of parallax errors (Ellsworth, 1928). A volume of 0.1 cc. is probably near the optimum for the smallest quantities of material consistent with the specified accuracy.

Experience of this investigation shows that the smallest internal diameter large enough to permit escape of bubbles when boiling under reduced pressure is 3.0 mm., as indicated in the figure. Toluene is used as the displacement fluid because its low surface tension facilitates the escape of bubbles.

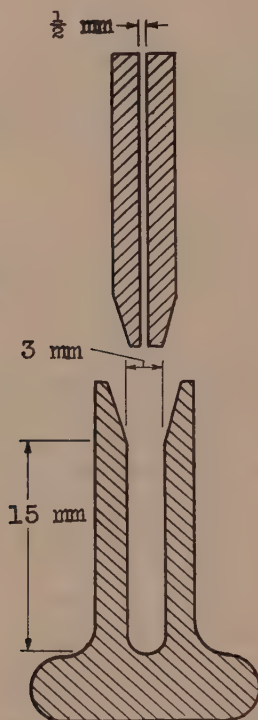


FIG. 1. Quartz-Glass Micropycnometer

PROCEDURE

The procedure adopted for use with this instrument is described below. One determination requires about an hour for an experienced operator.

1. Carefully selected material is powdered fine enough to pass a 1 mm. mesh; the very fine powder (about 130 mesh and smaller) is removed unless only a very small amount of material is available.

2. The weight of the clean, dry pycnometer is recorded in a form like that shown in Table 1; this is W_1 .

3. The weight of the pycnometer, $\frac{1}{2}$ to $\frac{2}{3}$ full of the prepared sample, is recorded as W_2 . $W_2 - W_1$ is the weight of the sample.

4. Toluene of known density (previously calibrated in a large Ellsworth-type pycnometer) is introduced, filling the pycnometer almost full. The contents are stirred with a capillary glass rod, removing most of the bubbles, and piling the grains along one side of the pycnometer tube, which is placed in a slanting position under a bell jar. The pressure is reduced until the liquid boils. Stirring and boiling may be repeated several times.

5. While the instrument is returning to room temperature after the boiling treatment, additional toluene is added, filling it to the top; the stopper is inserted, filling the capillary opening and forcing liquid out through it. Excess toluene is removed with filter paper. The weight, W_3 , is determined at the instant when the evaporation has brought the meniscus down opposite the scratch on the outside of the capillary. Several trials are usually necessary for this operation; the pycnometer must be refilled with toluene for each trial.

6. The temperature in the balance case is recorded opposite t .

7. The pycnometer is washed in acetone, dried by blowing out with compressed air, and weighed again. Its contents can be washed on a filter paper, dried, and later used as desired.

CALCULATION OF SPECIFIC GRAVITY

The data necessary for calculating the specific gravity of the powder are now at hand. The specific gravity of the toluene may be calculated from $s = a - bt$, where s = specific gravity of the toluene, a = specific gravity at 0° , b = the density coefficient, and t = the observed temperature. The constants a and b should be determined for each new lot of toluene; a is, in general, near 0.8810, b near 0.0010.

The formula for calculating the specific gravity of the powder can be expressed by

$$S = \frac{s(W_2 - W_1)}{W_2 + sv - W_3}$$

where S = specific gravity of the powder (unknown)

s = specific gravity of the toluene = $a - bt$ as already defined

W_1 = weight of the pycnometer, empty

W_2 = weight of the pycnometer with powder

W_3 = weight of the pycnometer with powder and liquid

v = volume of the pycnometer; previously determined using water or bromoform

The form shown in Table 1 facilitates making orderly calculations to which future reference can be made.

TABLE 1. FORM FOR CALCULATION OF DENSITY

Sphalerite, Santander			
W_2	5.9814	$sv+W_2$	6.0944
W_1	5.8272	W_3	6.0622
W_2-W_1	0.1542	$sv+W_2-W_3=D$	0.0322
t	24.5°C.	$\log (W_2-W_1)$	9.1881-10
s	0.8566	$\log s$	9.9328-10
sv	0.1130	$\text{colog } D$	1.4921
W_2	5.9814	$\log S$	0.6130
		S	4.1020

ACCURACY OF THE METHOD

Differentiating the equation and dividing by S , the relative error in the results may be obtained. This can be simplified to the following inequality:

$$\frac{dS}{S} < \frac{dW_1}{W_2-W_1} + \frac{dW_2+dW_3}{W_2+sv-W_3} + \frac{(W_2-W_1)ds}{(W_2+sv-W_3)s}$$

Assuming $dW = .0001$ gram, and $ds = .0002$,¹ we can evaluate the right side of the inequality for any trial. Using the example in Table 1 we find the first term is .00065, the second, .00621, and the third, .00059.

TABLE 2. TRIAL DENSITY DATA

	1*	2	3
	Pyrite	Sphalerite, Santander	Galena, Joplin
Number of trials	4	6	7
Highest specific gravity	5.11	4.16	7.69
Lowest specific gravity	4.23	3.95	7.60
Average specific gravity	4.60	4.09	7.64
Probable error of average	0.30	0.02	0.01
Probable error of 1 trial	0.60	0.05	0.02
Probable error of 1 trial	13.04%	1.22%	0.26%
Calculated maximum error (see text)	1.25%	0.71%	0.70%
Average weight of sample	0.1128 g.	0.1545 g.	0.2852 g.
Calculated specific gravity (x-ray data)	4.99	4.08	7.57

* Column 1 states results obtained using the method of centrifuging to remove air bubbles. Columns 2 and 3 state results using the method of boiling under reduced pressure, without the use of the centrifuge.

¹ As already stated, $s = a - bt$; therefore $ds = \pm bdt$. Hence, if the temperature is correct to 0.2°, $ds = .0002$.

The sum of these is .00745, of which the part due to temperature uncertainty is .00059, or less than .1 of the whole uncertainty. Even with a temperature uncertainty of .5°, this term is .00118 in a total of .00804.

It should be noted that the second term of this inequality contains the weight of the liquid in the pycnometer as part of the numerator, and the weight of liquid displaced by the powder as the denominator. This explains the advantage of using a micropycnometer nearly full of powder rather than a macropycnometer containing the same amount of powder in a relatively much larger container.

The above evaluation of the "maximum" error does not take account of air bubbles trapped in the powdered material by the liquid. To evaluate this added uncertainty, a series of trials on pyrite, sphalerite, and galena gave results indicated in Table 2. The data for pyrite were obtained using a centrifuge for the elimination of air bubbles from the pycnometer. The data for sphalerite and galena were obtained using the procedure outlined above.

For pyrite the probable error determined experimentally² is many times that calculated as a maximum for the conditions of the experiment, but for sphalerite and galena the probable error is very near that maximum (see Table 2). Therefore, the air bubbles were probably more successfully eliminated in the sphalerite and galena trials than in the pyrite trials. The consistency of the results is a recommendation for the procedure by which these results were obtained. Experiments using a more accurate balance might show a corresponding increase in accuracy; at present a probable error of 1% is assigned to any single random determination, or a correspondingly smaller probable error to the average of several such determinations.

ACKNOWLEDGMENT

The criticism and suggestions of Dr. Harry Berman are gratefully acknowledged. Dr. Berman gave valuable advice regarding both the design of the pycnometer and the preparation of the data. The financial backing of the Harvard Department of Mineralogy, through Professor

² If n observations of a quantity are represented by x_1, x_2, \dots, x_n , and their mean by \bar{x} , and their respective deviations from \bar{x} by d_i , then the probable error of any individual determination is

$$0.6745 \sqrt{\frac{\sum x_i^2}{n-1}}$$

and the probable error of the mean, \bar{x} , is

$$0.6745 \sqrt{\frac{\sum d_i^2}{n(n-1)}}$$

Charles Palache, made possible the pursuit of these experiments. Professor Palache's interest and encouragement greatly augmented the writer's patience during the early experiments on the design of the pycnometer.

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THE PARAGENESIS OF THE CENTER STRAFFORD, NEW HAMPSHIRE, PEGMATITE

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INTRODUCTION

About two miles northwest of Center Strafford, in southeastern New Hampshire, a pegmatite is quarried for feldspar and mica. It is especially interesting for its abundance of unusual phosphates; in particular triphylite, graftonite, fairfieldite, and a number of their alteration products. Also noteworthy is the relative abundance of loellingite. These complex constituents make up only about 10 per cent of the pegmatite, microcline, muscovite, and quartz constituting the remainder.

THE PEGMATITE

The granitic body of which the Center Strafford pegmatite is a portion, is post-Carboniferous in age, being part of a group of granites and granite-gneiss considered by F. J. Katz (1917) to be equivalent to the Biddeford granite of southwestern Maine. In the vicinity of Center Strafford the granite has intruded schists and phyllites of Carboniferous (Pennsylvanian?) age.

The pegmatite is roughly lenticular in shape, the lens-shaped mass standing almost on edge, and is located on the side of a steep slope. The widest part is about 40 feet in width. The floor of the quarry is flat and cuts into the hill 150 feet, where it rapidly wedges out. The walls of the present quarry at its head are about 50 feet high. According to the present operator, Mr. Buzzo, of Center Strafford, a water-filled pit at the head of the quarry goes down an additional 60 or 70 feet, and presumably reached the bottom of the lens.

The pegmatite is enclosed in a wall rock of distinctly gneissic granite almost lacking in ferromagnesium minerals. Within a few feet of the pegmatite border the granite contains a small amount of black tourmaline, and at the border there is a noticeable concentration of tourmaline several inches wide.

The wall rock is uniformly fine grained and makes a sharp boundary with the pegmatite. Along the northeast border of the pegmatite is a band of typical graphic granite from several inches to a foot or more in width. The graphic granite is in sharp contact with the gneissic wall rock on one side and the typical coarse grained pegmatite on the other and is entirely confined to this peripheral zone. Coarse microcline crystals with large masses of anhedral quartz make up most of the body of the pegmatite, but none of this microcline shows a graphic quartz intergrowth.

The minerals introduced into the pegmatite during the pneumatolytic and hydrothermal stages are limited in position entirely to the southeast pegmatite-wall rock contact, indicating that there was a through-going channel along the contact to which the mineralizing vapors and solutions had access.

PARAGENESIS

There were three distinct stages of mineralization at Center Stratford. The first, or primary stage, represents the crystallization of a rest-magma not greatly different in composition from a normal granitic magma. The peripheral zones of graphic granite and tourmaline, and the coarsely crystalline microcline, muscovite, and quartz of the main pegmatite body crystallized at this time.

The second stage of mineralization has been termed pneumatolytic, since it apparently represents a high temperature stage of mineralization by magmatic emanations rich in volatile constituents. Large quantities of beryl, triphylite, apatite, and albite were introduced at this time, almost entirely by a replacement process.

TABLE 1. SEQUENCE OF MINERALIZATION

Magmatic	Microcline	KAlSi_3O_8
	Muscovite	$\text{KAl}_2(\text{Si, Al})_4\text{O}_{10}(\text{OH})_2$
	Tourmaline	$\text{Na}(\text{Fe, Mg})_3\text{B}_3\text{Al}_3(\text{Al}_3\text{Si}_6\text{O}_{27})(\text{OH})_4$
	Quartz	SiO_2
Pneumatolytic	Beryl	$\text{Al}_2\text{Be}_3\text{Si}_6\text{O}_{18}$
	Triphylite	$\text{Li}(\text{Fe, Mn})\text{PO}_4$
	Graftonite	$(\text{Fe, Mn, Ca})_3\text{PO}_4$
	Manganapatite	$(\text{CaF})\text{Ca}_4(\text{PO}_4)_3$ with Mn
	Albite	$\text{NaAlSi}_3\text{O}_8$
Hydrothermal	Amblygonite	$\text{LiAl}(\text{F, OH})\text{PO}_4$
	Rhodochrosite	MnCO_3
	Fairfieldite	$\text{Ca}_2\text{Mn}(\text{PO}_4)_2 \cdot 2\text{H}_2\text{O}$
	Microcline	KAlSi_3O_8
	Quartz	SiO_2
	Columbite	$(\text{Fe, Mn})(\text{Nb, Ta})_2\text{O}_6$
	Muscovite	$\text{KAl}_2(\text{Si, Al})_4\text{O}_{10}(\text{OH})_2$
	Garnet	$(\text{Fe, Mn})_3\text{Al}_2(\text{SiO}_4)_3$
	Loellingite	FeAs_2
Low temperature hydrothermal	Cassiterite	SnO_2
	Autunite	$\text{Ca}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$
	Vivianite	$\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$
	Eosphorite	$\text{AlPO}_4 \cdot (\text{Mn, Fe})(\text{OH})_2 \cdot \text{H}_2\text{O}$
	Heterosite	$(\text{Fe, Mn})\text{PO}_4 \cdot \text{H}_2\text{O}$
	Ferri-sicklerite (?)	$\text{Li}(\text{Mn, "Fe"})\text{PO}_4$

The third, or hydrothermal stage of mineralization, resulted in the progressive introduction of a large number of minerals by hydrothermal solutions. The most abundant of these are rhodochrosite, quartz, muscovite, garnet, and loellingite. The hydrothermal stage is considered to have been an essentially continuous period of replacement, during which the temperature of the solutions gradually fell. The final action of the solutions, as their temperature approached that of meteoric waters near the surface was an alteration of previously formed minerals. The most abundantly altered mineral was triphylite, which changed to several hydrous iron and manganese phosphates.

DESCRIPTION OF THE MINERALS

Microcline. Microcline-perthite is the most abundant mineral in the pegmatite, where it occurs in rough subhedral crystals up to two feet across. On the border of the pegmatite it is intergrown with quartz as graphic granite. The perthite lamellae are about one half to one mm. wide, and spaced two to three mm. apart.

A small amount of hydrothermal microcline has formed in narrow veins with albite and amblygonite, cutting triphylite.

Muscovite. Muscovite of two generations is clearly represented. The primary muscovite was one of the earliest formed minerals. It occurs as subhedral crystals up to one foot across, and several inches thick entirely enclosed in microcline. However, there is no evidence for replacement, but rather, a complete overlap of the period of crystallization of feldspar over that of muscovite.

A pipe-like mass of muscovite approximately 10 feet in diameter and 20 feet high, near the head of the quarry, has clearly replaced a mass of microcline and quartz. The muscovite crystals in this case are smaller, and the interstices between them are occupied by remnants of the replaced microcline and quartz.

Tourmaline. All the tourmaline seen was the black iron-rich variety, which occurs in prismatic crystals up to 4 cm. in length and 2 cm. in diameter. Its occurrence is almost entirely confined to the border of the pegmatite. Within the main body of the pegmatite it is found as small flattened crystals within large crystals of muscovite. They are most commonly flattened parallel to a prism face. Figure 1 illustrates a tourmaline crystal of this type flattened parallel to $a\{11\bar{2}0\}$. The other forms present are $m\{10\bar{1}0\}$, and $r\{10\bar{1}1\}$. There seems to be no definite oriented intergrowth of the tourmaline and muscovite, other than that the direction of flattening of the tourmaline crystals is always parallel to the basal cleavage of the muscovite.

Quartz. Quartz was the last magmatic mineral to crystallize. It forms

large anhedral masses interstitial to the microcline. It is colorless, or slightly smoky, and has been badly shattered and stained by iron and manganese oxides.

Quartz of a later generation is indicated by narrow veins cutting triphylite and albite, and therefore post-albite.

Beryl. Pale green to white beryl occurs in considerable abundance as rather large crystals. The largest crystal exposed on the quarry wall was about one foot in diameter and two feet long. Crystals from two to six inches in diameter were quite abundant on the west wall of the quarry. The crystals generally occur imbedded in badly fractured masses of quartz, and have often been partially replaced by apatite and albite.

Triphylite. A nodular mass of triphylite of unusual size was developed at Center Strafford. The mass was approximately 10 feet across. The

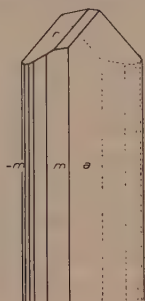


FIG. 1. Flattened Crystal of Tourmaline

triphylite is medium brown in color, showing large fresh cleavage surfaces but rarely any crystal outline. One rough prism section was found, about 3 cm. across, almost entirely altered to a hydrous manganese oxide.

Table 2 gives the results of an analysis of this triphylite.

The Center Strafford triphylite is orthorhombic, exhibits one perfect cleavage, $\{001\}$, and a less perfect cleavage at right angles to the first, $\{010\}$. The fracture is conchoidal. It contains abundant minute inclusions oriented parallel to the cleavages, of unknown nature. It has the following optical properties, which are in very close agreement with those given by Larsen and Berman (1934) for a triphylite with 26.85 per cent FeO.

	M	
$X=c$	1.686	Biaxial (+), $2V=20^\circ$
$Y=a$	1.687	
$Z=b$	1.693	
		± 0.002
		Dispersion very strong, $r > v$.

Graftonite. The rare mineral graftonite occurs in small reddish brown

TABLE 2. ANALYSIS AND MOLECULAR RATIOS OF TRIPHYLITE

	1.	2.	3.	4.
FeO	29.13	29.05	0.4044	29.38
MnO	15.96	15.92	0.2245	16.06
MgO	0.42	0.42	0.0104	
CaO	0.31	0.31	0.0055	
Li ₂ O	8.86	8.84	0.2957	9.46
Na ₂ O	0.15	0.15	0.0024	
K ₂ O	0.07	0.07	0.0007	
P ₂ O ₅	44.87	44.76	0.3116	45.10
H ₂ O	0.48	0.48	0.0300	
Insol.	0.21			
	100.46	100.00		100.00

1. Center Strafford triphylite, F. A. Gonyer, analyst.

2. Analysis calculated to 100%, after deducting insolubles.

3. Molecular ratios.

4. Calculated composition for $\text{Li}(\text{Fe}, \text{Mn})\text{PO}_4$, with $\text{Fe}:\text{Mn}=1.72:1$.

intergrowths with triphylite. This mineral has previously been described from Grafton, New Hampshire, by S. L. Penfield (1900), from North Groton, New Hampshire by H. Berman (1927), and most recently from Greenwood, Maine, by J. J. Glass and J. J. Fahey (1937). In the first two localities it occurred interlaminated with triphylite, probably as a simultaneous crystallization. This same relationship seems to hold at Center Strafford, although the evidence is not clear. The optical properties of the Center Strafford graftonite correspond closely to those given by Berman for graftonite from North Groton, and are as follows:

	ⁿ	
X	1.700	} ± 0.002
Y	1.706	
Z	1.726	
		Biaxial (+), $2V=50^\circ$
		Dispersion strong, $r > v$.

Manganapatite. This mineral occurs commonly in the pegmatite in dark green, transparent, anhedral masses, or less commonly as opaque brown crystals. Both color varieties contain manganese, and are uniaxial (—), with $\omega=1.632 (\pm 0.002)$.

Albite. The platy form of albite commonly termed cleavandite is an abundant mineral of the pegmatite, having replaced large quantities of microcline, and some quartz, beryl, triphylite, and apatite.

Amblygonite. Amblygonite was found only in small amounts associated with albite and microcline in narrow veins cutting triphylite. It is visible

only in thin section, where it is easily recognizable because of polysynthetic twinning together with high birefringence.

Rhodochrosite. Pale pink, fine grained rhodochrosite occurs in veins cutting triphylite. In several instances it has been partially replaced by loellingite. It is uniaxial (—), with $\omega = 1.832 (\pm 0.003)$.

Fairfieldite. Fairfieldite, identified optically, occurs as pale salmon pink, fine grained masses with rhodochrosite and triphylite.

Columbite. Columbite, identified by its appearance under the microscope and its specific gravity ($D = 5.46$), occurs widely scattered throughout the pegmatite in small poorly developed, tabular crystals, commonly associated with the second generation quartz, but it can be definitely dated only as post-albite.



FIG. 2. Crystal of Loellingite

Garnet. Garnet was found in a single mass several feet in diameter, and nowhere else in the pegmatite. Part of the garnet has replaced some of the second generation muscovite, and both were later partially replaced by loellingite. A refractive index of 1.790 and a specific gravity of 4.14 indicate the garnet to be almandite-spessartite. It is red in color, and completely isotropic. It occurs as individual crystals up to 2 inches in diameter, the dodecahedron being the most common form. Occasionally the trapezohedron $n\{211\}$ has developed.

Loellingite. The sulphide-rich stage at Center Strafford was characterized by an abundance of loellingite. It is tin white in color, sometimes tarnished brown. It occurs in rough prismatic crystals up to 5 cm. in length, and in irregular crystalline masses. Rarely small crystals, up to 2 mm. in length, have developed in considerable perfection. Such a crystal is illustrated in Fig. 2. The forms present are: $m\{110\}$, $l\{011\}$, and $z\{012\}$. The base $c\{001\}$ is sometimes present.

The presence of loellingite in the pegmatite is almost entirely confined to the concentrations of triphylite, muscovite, and garnet previously described, and it has replaced all three of these minerals.

Table 3 gives the results of an analysis of this loellingite.

TABLE 3. ANALYSIS AND MOLECULAR RATIOS OF LOELLINGITE

	1.	2.	3.	4.
Fe	27.89	27.95	0.5011 = 1×0.5011	27.18
As	70.94	71.09	1.054	
S	0.96	0.96	0.030 } = 2×0.542	72.82
	99.79	100.00		100.00

1. Loellingite from Center Strafford, F. A. Gonyer, analyst.

2. Composition calculated to 100%.

3. Molecular ratios.

4. Calculated composition for FeAs_2 .

Cassiterite. Cassiterite in rough crystals up to one cm. across occurs in small amounts in triphylite and quartz, and replacing loellingite. The pleochroism is distinct, ω = colorless, ϵ = dark reddish brown. Pleochroism is a property not commonly given for cassiterite, and is generally noted only in pegmatitic material.

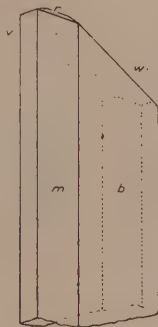


FIG. 3. Crystal of Vivianite

Autunite. Autunite occurs as small pale green flakes on quartz, feldspar, or muscovite. It fluoresces a strong yellowish green under an ultra-violet light source.

Vivianite. Vivianite is one of the most common triphylite alteration products. It occurs as thin films along cleavage planes of the triphylite, or as small masses of powdery material, and rarely as small rough crystals. A typical crystal is shown in Fig. 3. It is monoclinic, with the forms $b\{010\}$, $m\{110\}$, $v\{\bar{1}11\}$, $w\{\bar{1}01\}$, and $r\{\bar{1}12\}$. The mineral is deep blue in color, and strongly pleochroic from deep blue to colorless, conforming with known optical properties for this mineral.

Eosphorite. Eosphorite occurs as small, pale brown, poorly formed crystals on triphylite or its alteration products. Its optical properties correspond closely to those of eosphorite from Branchville, Connecticut (Larsen and Berman, 1934). Eosphorite from Center Stafford has the following optics:

	n	
X	1.640	} ± 0.002
Y	1.662	
Z	1.666	
		Biaxial (-), $2V=35^\circ$
		Dispersion perc., $r > v$.

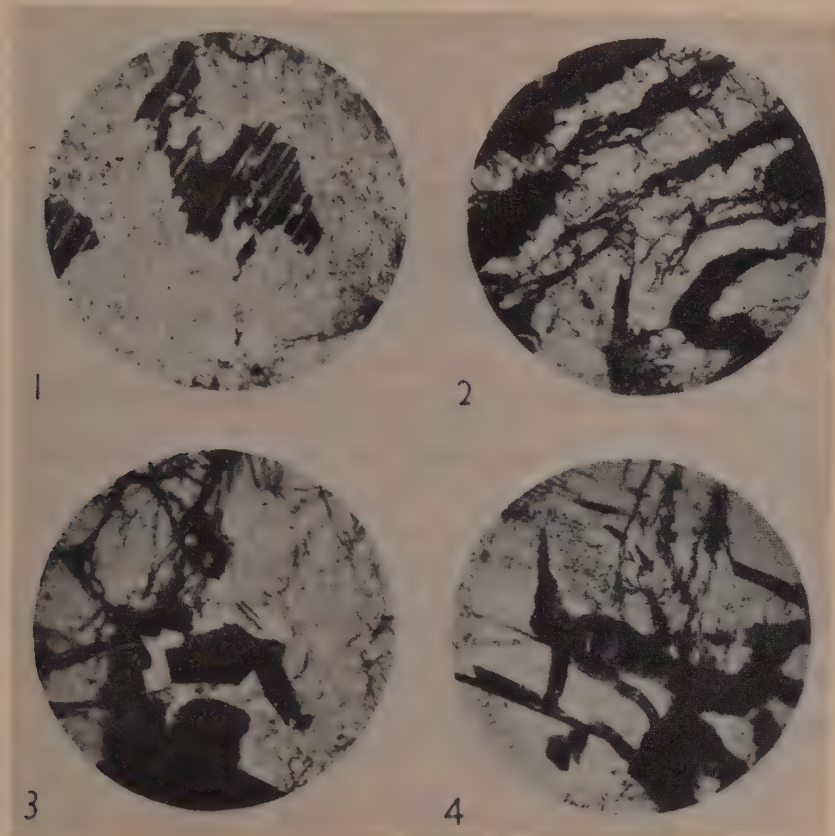
Heterosite. Heterosite occurs as an alteration product of triphylite. It is nearly black in the mass, with a dark red powder. It is optically negative, with a moderate optic angle, has a mean refractive index of about 1.84, and a high birefringence. It is strongly pleochroic from greenish grey to deep red.

Other alteration products. Quensel (1937) has described an alteration product of triphylite from the lithium pegmatite of Varutrask, Sweden, which resembles sicklerite, but has a much higher content of iron, and higher indices of refraction. He called this mineral ferri-sicklerite to distinguish it from sicklerite as described by W. T. Schaller (1912). One of the triphylite alterations from Center Strafford resembles Quensel's ferri-sicklerite, and it may be that the two are the same. In a direct comparison of the material in question from Center Strafford, and ferri-sicklerite from Varutrask kindly furnished by Dr. Quensel, the two minerals resemble each other rather closely both physically and optically. The Center Strafford material is dark brown or black in color, and has a dark brown powder. It is biaxial, with a moderate optic angle, has a mean refractive index of approximately 1.80, and is strongly pleochroic from light to dark brown. Due to high absorption, optical data are obtained with great difficulty, so the exact optical correspondence of the two is not certain.

A specimen from Center Strafford, collected by Mr. Gunnar Bjareby, of Boston, Massachusetts, contained a mineral as yet unidentified. It occurs as small botryoidal masses of radiating fibres, clearly an alteration of triphylite. It most closely resembles dufrenite, but its indices of refraction are much lower, and its pleochroism more intense. Qualitatively it was found to be essentially a hydrous phosphate of iron and manganese. The following optical properties were determined:

	n	
X	1.787	} ± 0.003
Y parallel to elong. fibres	1.813	
		Biaxial (+), $2V=85^\circ$
		Pleochroism: X=bright green
		Y=reddish brown

The three minerals just described, heterosite and the two uncertain alteration products, are apparently members of an alteration series from pure or slightly altered triphylite to the final end products of alteration,



- (1) Amblygonite, showing polysynthetic twinning. Crossed nicols. 28×
- (2) Muscovite (dark grey) and loellingite (black) replacing triphylite (light grey). Crossed nicols. 20×
- (3) Loellingite (black) replacing muscovite (light grey) and garnet (dark grey). Ordinary light. 20×
- (4) Triphylite (light) altering to ferri-sicklerite(?) (dark). Ordinary light. 20×

hydrous manganese and iron oxides. Samples examined from various parts of a small mass will vary greatly in their indices of refraction, and other optical and physical properties. It was found, therefore, impractical to deal with this material in a detailed manner.

SUMMARY

The Center Strafford pegmatite is a lens shaped body enclosed in a gneissic wall rock, which it has intruded. The main body of the pegmatite, composed of microcline and quartz, has formed by crystallization of a rest-magma. The complex constituents have been introduced by an extensive replacement process. Beryl, triphylite, graftonite, manganapatite, and albite were the first of these, and have been classified as pneumatolytic, since they appear to have been introduced by vapors or solutions high in volatile constituents. Following these and apparently deposited by true hydrothermal solutions, were a number of minerals, the most abundant of which were rhodochrosite, muscovite, garnet, and loellingite. As the temperature of the solutions approached those of near surface meteoric waters, the earlier formed phosphates were extensively altered to vivianite, eosphorite, heterosite, and others.

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CRYSTALLOGRAPHIC STUDIES OF SULPHOSALTS:
BAUMHAUERITE, MENEGHINITE, JORDANITE,
DIAPHORITE, FREIESLEBENITE

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WITH X-RAY STUDIES BY
W. E. RICHMOND AND HORACE WINCHELL

BAUMHAUERITE

Information regarding this mineral is confined to the paper of Solly (1903). The author measured two crystals and from the gnomonic plot of one of them discovered a typographical error in Solly's original statement of the axial ratio. This error did not affect the values of his angles but it has gone into every printed description of the mineral. Since no complete two-circle angle table has been published for baumhauerite, one has been calculated and the angles for the more important forms are given below; 118 forms are listed by Solly whose position and elements (corrected) have been used. The mineral is characterized by the enormous development of the orthodome zone to which belong two-thirds of the observed forms.

BAUMHAUERITE— $\text{Pb}_4\text{As}_6\text{S}_7$

Monoclinic; prismatic— $2/m$

$a:b:c=1.3687:1:0.9472$; $\beta=97^\circ 17'$

$p_0:q_0:r_0=0.6920:0.9396:1$; $\mu=82.43$

$r_2:p_2:q_2=1.0643:0.7365:1$;

$p_0'=0.6976$, $q_0'=0.9472$; $x_0'=0.1278$

Forms	ϕ	ρ	ϕ_2	$\rho_2=B$	C	A
<i>c</i> 001	90°00'	7°17'	82°43'	90°00'	0°00'	82°43'
<i>b</i> 010	0 00	90 00	—	0 00	90 00	90 00
<i>a</i> 100	90 00	90 00	0 00	90 00	82 43	0 00
<i>F</i> 520	61 29½	90 00	0 00	61 29½	83 36	28 30½
<i>H</i> 210	55 49½	90 00	0 00	55 49½	83 59	34 10½
<i>K</i> 320	47 51	90 00	0 00	47 51	84 36½	42 09
<i>m</i> 110	36 22½	90 00	0 00	36 22½	85 41½	53 37½
<i>O</i> 120	20 13	90 00	0 00	20 13	87 29½	69 47
<i>k</i> 011	7 41	43 42½	82 43	46 47	43 13	84 42
<i>ι</i> 702	90 00	68 44	21 16	90 00	61 27	21 16
<i>κ</i> 301	90 00	65 45½	24 14½	90 00	58 28½	24 14½
<i>μ</i> 502	90 00	61 53	28 07	90 00	54 36	28 07

BAUMHAUERITE—Continued

Forms	ϕ	ρ	ϕ_2	$\rho_2=B$	C	A
ξ 201	90 00	56 42½	33 17½	90 00	49 25½	33 17½
ρ 302	90 00	49 35	40 25	90 00	42 18	40 25
ψ 101	90 00	39 32	50 28	90 00	32 15	50 28
Λ 102	90 00	25 29	64 31	90 00	18 12	64 31
Π 103	90 00	19 49	70 11	90 00	12 32	70 11
Σ 104	90 00	16 49	73 11	90 00	9 32	73 11
Φ 106	90 00	13 43	76 17	90 00	6 26	76 17
g : $\bar{1}04$	—90 00	2 40	92 40	90 00	9 57	92 40
l : $\bar{1}02$	—90 00	12 27½	102 27½	90 00	19 44½	102 27½
q : $\bar{1}01$	—90 00	29 40½	119 40½	90 00	36 57½	119 40½
t : $\bar{3}02$	—90 00	42 34	132 34	90 00	49 51	132 34
w : $\bar{7}04$	—90 00	47 32½	137 32½	90 00	54 49½	137 32½
z : $\bar{2}01$	—90 00	51 43½	141 43½	90 00	59 00½	141 43½
C : $\bar{5}02$	—90 00	58 15	148 15	90 00	65 32	148 15
E : $\bar{3}01$	—90 00	63 01½	153 01½	90 00	70 18½	153 01½
p 111	41 04	51 29	50 28	53 51	46 56	59 04
o $\bar{1}11$	—31 02	47 52	119 40½	50 33	51 54	112 28½
n 122	26 42½	46 40½	64 31	49 28	43 46½	70 55
N $\bar{1}22$	—13 08	44 12½	102 27½	47 14	46 17½	99 07

Errata: Solly (1903) for $a=1.1368$ read 1.3687

Dana (1909) for $a=1.1368$ read 1.3687

Goldschmidt (1928) for $p_0'=0.8402$ read 0.6976;

for $e'=0.1305$ read 0.1278

for $p_0=0.8332$ read 0.6920;

for $\mu=82^\circ34'$ read $82^\circ43'$

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MENECHINITE

Meneghinite has been found in definite crystals at but one locality, Bottino, Italy. Our knowledge of its crystallography rests upon studies made simultaneously by Krenner (1883) and Miers (1883), which estab-

lished its orthorhombic character and yielded substantially the same elements. The two authors differed, however, in one respect. Miers found a series of typical forms with simple indices and with them additional forms of equally good quality to which he could only assign very complex indices. He insisted that these forms were to be regarded as true members of the form series. Krenner also observed such forms but regarded them as vicinal and discarded them. He pointed out that such vicinal forms accounted for the earlier erroneous monoclinic interpretation of the crystals by vom Rath (1867).

No further observations seem to have been made on meneghinite; but Ungemach (1923) discussed the form series, suggested a new choice of unit form and concluded that the aberrant forms might be best explained by regarding the mineral as monoclinic with concealed twinning, analogous to jordanite with which isomorphism had been suspected by several authors.

The author tested this theory by measuring crystals, and Mr. W. E. Richmond made an x -ray study which is reported below. The results of these studies are positive as to the orthorhombic character of meneghinite; a new unit cell is imperative which differs from that of any previous observer; the aberrant forms are confirmed but wholly unexplained; and the fact is established that it is not isomorphic with jordanite.

The crystals are slender needles with minute terminal facets. The acicular direction is taken as c by all observers. The new elements required by the x -ray measurements have the same directions as before, but the new unit (111) is the form (414) of Miers and (214) of Krenner. Transformations:—

Miers to Palache $\frac{1}{4}00/010/00\frac{1}{4}$

Krenner to Palache $\frac{1}{2}00/010/00\frac{1}{4}$

As the basis of the angle table, the author has employed the elements of Goldschmidt (1897), which are the mean of those of Miers and Krenner. Table 1 is therefore a restatement of Goldschmidt's angles with new indices for the forms; the letters have been preserved unchanged except for two prisms.

The author measured three crystals from the type locality. They show a prism zone so deeply grooved by striations that but a few typical faces could be recognized except the pinacoid parallel to which there is perfect cleavage. This face, always good, was taken as (010). The presence of basal cleavage was also verified, but both cleavages are obtained only with considerable difficulty. Table 2 shows the terminal faces found on two of the measured crystals.

TABLE 1. MENECHINITE— $\text{Pb}_{13}\text{Sb}_7\text{S}_{23}$

Orthorhombic; dipyramidal— $m\ m\ m$						
$a:b:c=0.4736:1:0.1715$; $p_0:q_0:r_0=0.3621:0.1715:1$ $q_1:r_1:p_1=0.4736:2.7617:1$; $r_2:p_2:q_2=5.8309:2.1114:1$						
Forms	ϕ	$\rho=C$	ϕ_1	$\rho_1=A$	ϕ_2	$\rho_2=B$
<i>c</i> 001	—	0°00'	0°00'	90°00'	90°00'	90°00'
<i>b</i> 010	0°00'	90 00	90 00	90 00	—	0 00
<i>a</i> 100	90 00	90 00	—	0 00	0 00	90 00
<i>e</i> 160	19 23	90 00	90 00	70 37	0 00	19 23
<i>R</i> 140	27 49½	90 00	90 00	62 10½	0 00	27 49½
<i>S</i> 130	35 08	90 00	90 00	54 52	0 00	35 08
<i>l</i> 380	38 22	90 00	90 00	51 38	0 00	38 22
<i>f</i> 5.12.0	41 20	90 00	90 00	48 40	0 00	41 20
<i>T</i> 120	46 33	90 00	90 00	43 27	0 00	46 33
<i>g</i> 340	57 43	90 00	90 00	32 17	0 00	57 43
<i>i</i> 780	61 34½	90 00	90 00	28 25½	0 00	61 34½
<i>m</i> 110	64 39½	90 00	90 00	25 20½	0 00	64 39½
<i>h</i> 520	79 16½	90 00	90 00	10 43½	0 00	79 16½
<i>k</i> 310	81 01½	90 00	90 00	8 58½	0 00	81 01½
<i>y</i> 032	0 00	14 25½	14 25½	90 00	90 00	75 35½
<i>d</i> 021	0 00	18 56	18 56	90 00	90 00	71 04
<i>o</i> 083	0 00	24 35	24 35	90 00	90 00	65 25
<i>v</i> 041	0 00	34 27½	34 27½	90 00	90 00	55 32½
<i>n</i> 101	90 00	19 54½	0 00	70 05½	70 05½	90 00
<i>W</i> 403	90 00	25 46½	0 00	64 13½	64 13½	90 00
<i>V</i> 201	90 00	35 55	0 00	54 05	54 05	90 00
<i>u</i> 111	64 39½	21 50	9 44	70 21½	80 05½	80 50½
β 221	64 39½	38 42½	18 56	55 35	54 05	74 28½
<i>t</i> 121	46 33	26 30½	18 56	71 05½	80 05½	72 07½
<i>s</i> 131	35 08	32 11	27 14	72 09	80 05½	64 11
<i>r</i> 141	27 49½	37 48½	34 27½	73 22½	80 05½	57 10½
μ 211	76 40½	36 39½	9 44	54 29	54 05	82 05½
<i>p</i> 241	46 33	44 56	34 27½	59 09	54 05	60 56½
δ 0.24.13	0 00	17 34	17 34	90 00	90 00	72 26
ϕ 0.24.11	0 00	20 31½	20 31½	90 00	90 00	69 28½
<i>q</i> 24.0.11	90 00	38 19	0 00	51 41	51 41	90 00
λ 24.24.13	64 39½	36 29½	17 34	57 29½	56 14	75 15
σ 24.24.11	64 38½	41 09½	20 31	53 30	51 41	73 38

TABLE 1.—*Continued*

Forms	ϕ	$\rho=C$	ϕ_1	$\rho_1=A$	ϕ_2	$\rho_2=B$
ρ 24.48.11	46 33	47 25½	36 49	57 41	51 41	59 34½
ψ 24.48.13	46 33	42 38½	32 21	60 32½	56 14	62 14
X 24.72.13	35 08	49 16½	43 32	64 08½	56 14	51 42
π 24.96.13	27 49½	55 04½	51 42½	67 30	56 14	43 31
ω 7.21.1	35 08	77 12½	74 29	55 52	21 32	37 06

TABLE 2. MEASUREMENTS OF MENEGHINITE

Crystal 1	Measured		Calculated		Quality
	ϕ	ρ	ϕ	ρ	
010	0°00'	90°00'	0°00'	90°00'	excellent
0.24.11	0 00	20 07	0 00	20 31½	good
121	46 37	26 35	46 33	26 30½	excellent
24.24.13	64 32	36 40	64 39½	36 29½	poor—end of chain
Crystal 2					
010	0 00	90 00	0 00	90 00	excellent
041	0 02	34 36	0 00	34 27½	excellent
0.24.11	0 02	20 35	0 00	20 31½	good
111	65 16	21 36	64 39½	21 50	very poor
121	46 22	26 52	46 33	26 30½	poor
131	35 09	32 11	35 08	32 11	excellent
141	28 04	38 00	27 49½	37 48½	poor
$\bar{1}41$	—28 00	37 55	—27 49½	37 48½	good
211	76 45	37 10	76 40½	36 39½	very poor
$\bar{2}11$	—76 32	37 00	—76 40½	36 39½	very poor
241	46 22	43 35	46 33	44 56	very poor
24.24.13	65 16	36 44	64 39½	36 29½	poor
$\bar{2}4.24.13$	—64 32	36 34	—64 39½	36 29½	good
24.24.11	65 16	41 31	64 39½	41 09½	poor
$\bar{2}4.24.11$	—64 32	41 04	—64 39½	41 09½	poor
24.48.13	46 32	42 50	46 33	42 38½	excellent
7.21.1	35 32	77 12	35 08	77 12½	poor
7.21.1	35 09	76 43	—35 08	77 12½	poor

This table shows clearly that each of these crystals has faces of both normal and aberrant forms, intermingled and all in good position. There is no difference observable in quality between them and in no way could one say that one set was more typical than the other. All the faces are so minute that it is difficult to observe the actual crystal surfaces. It is noteworthy that the aberrant forms are displaced by small angular distances, from faces of simple indices but always in a radial relation, the ϕ angles being alike. It is difficult to picture this relation as being due to any type of twinning.

Two new forms were noted as shown in the table, (0.24.11) and (7.21.1), each with two faces. They are simply to be added to the list of aberrant forms. Q and w , listed in Miers from vom Rath are omitted as very uncertain.

The third crystal measured showed no trace of aberrant forms but yielded a characteristic series in good position, including (010), (100), (140), (380), (120), (110), (021), (041), (101), (111), (121), (131), and (141).

STRUCTURAL LATTICE OF MENEGHINITE

by W. E. RICHMOND

The structural lattice was determined from rotation and Weissenberg photographs about the needle axis [001]. The lattice constants computed from the x -ray photographs are:

$$a_0 = 11.29; b_0 = 23.78; c_0 = 4.12$$

giving the ratio:—

$a:b:c = 0.4750:1:0.1733$ in close agreement with the morphological ratio:—

$$a:b:c = 0.4736:1:0.1715.$$

The volume of the unit cell $V_0 = 1103$; with the specific gravity 6.358 (vom Rath) this gives a molecular weight for the unit cell of $M_0 = 4162$.

The content of the unit cell. The analysis of meneghinite by vom Rath has the smallest amount of impurity, so is made the basis of the calculation as shown in the following table.

TABLE 3. ANALYSIS OF MENEGHINITE

	1	2	3	4	5	6
Pb	61.47	63.75	.308	13.08	63.92	62.88
Sb	18.37	19.05	.156	6.68	18.77	19.91
S	16.97	17.20	.537	22.85	17.31	17.21
Cu	0.39					
Fe	0.23					
Ins.	0.82					
	98.25	100.00			100.00	100.00

1. Meneghinite from Bottino, Italy. Vom Rath, analyst.
2. Recalculated to 100% after deducting CuFeS_2 and insoluble.
3. Atomic proportions of 2.
4. Atomic content of unit cell.
5. Calculated composition of formula $\text{Pb}_4\text{Sb}_2\text{S}_7$.
6. Calculated composition of formula $\text{Pb}_{13}\text{Sb}_7\text{S}_{23}$.

The figures of column 4 yield the formula $\text{Pb}_{13}\text{Sb}_7\text{S}_{23}$, replacing the old accepted formula $\text{Pb}_4\text{Sb}_2\text{S}_7$. The density calculated for this formula is 6.391, which compares favorably with the value of vom Rath, 6.358.

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JORDANITE

The latest account of jordanite is contained in the paper by Solly (1900), in which he traces the history of the mineral to that time and adds new forms to the already long lists of Baumhauer. Solly employs the position and elements of the latter, namely:

$$a:b:c=0.4945:1:0.2655 \quad \beta=90^\circ 33\frac{1}{2}'$$

The author measured two crystals from the type locality, confirming the angles and many of the forms of earlier observers and adding five new forms. The crystals were measured with (010) as pole, and the gnomonic projection at once suggested both to the author and to Dr. Peacock a possible better choice of orientation of the axes. The choice

finally made by Peacock on a morphological basis was confirmed, as is shown below, by x -ray study and is accepted as the proper setting.

The new axial ratio, calculated from the old, is:

$$a:b:c = 0.2354:1:0.1397 \quad \beta = 93^\circ 53'$$

and its position is related by the transformations

Baumhauer to Peacock	$\overline{1}03/0\overline{4}0/101$
Peacock to Baumhauer	$\overline{1}03/010/101$

This is equivalent to taking (100) Baumhauer as ($\overline{1}01$)
 (010) Baumhauer as ($0\overline{1}0$)
 (001) Baumhauer as (301)

Twinning referred to the new axes is most common on {100} and is often lamellar, yielding a surface of parting; it is common on {001}, rare on {101} and very rare on {301}.

Cleavage is parallel to {010}, which is the direction of dominant tabular development.

The following forms of Solly's list are omitted, being regarded as vicinal to closely neighboring forms:

Form Solly	Palache	Vicinal to	Diff. in angle to (010)
(12.49.0)	(3.49.3)	($\overline{1}$.16.1)	28 minutes
(9.32.0)	(9.128.9)	($\overline{1}$.14.1)	23 minutes
(7.24.0)	(7.96.7)	($\overline{1}$.14.1)	31 minutes
(047)	(21.16.7)	(321)	84 minutes
(28.3.28)	(28.3.0)	(910)	3 minutes

The following forms are added to the list on the basis of the author's observations:

Symbol		Measured		Calculated	
Palache	Solly	ϕ	ρ	ϕ	ρ
(091)	(391)	$\left\{ \begin{array}{l} 85^\circ 57' \\ 86^\circ 09' \end{array} \right.$	$\left\{ \begin{array}{l} 38^\circ 30' \\ 38^\circ 32' \end{array} \right.$	$86^\circ 07'$	$38^\circ 33\frac{1}{2}'$
(183)	(221)	74 52	70 32	75 05 $\frac{1}{2}$	70 12
(1.54.1)	(1.28.1)	56 37	9 42	56 28	9 02
(3.14.1)	(371)	150 04	45 19	149 46 $\frac{1}{2}$	45 27
(3.16.1)	(381)	150 00	41 37	149 46 $\frac{1}{2}$	41 38

Because no complete angle table has been calculated for jordanite since it was determined to be monoclinic, the author has calculated such a table and gives herewith some of the more important forms. There are 115 forms known.

TABLE 1. JORDANITE— $\text{Pb}_{14}\text{As}_7\text{S}_{24}$

Monoclinic; prismatic— $2/m$ $a:b:c=0.2354:1:0.1397$; $\beta=93^\circ53'$ $p_0:q_0:r_0=0.5935:0.1394:1$; $\mu=86^\circ07'$ $r_2:p_2:q_2=7.1747:4.2579:1$; $p_0'=0.5948$, $q_0'=0.1397$; $x_0'=0.0679$						
Forms	ϕ	ρ	ϕ_2	$\rho_2=B$	C	A
<i>b</i> 010	0°00'	90°00'	—	0°00'	90°00'	90°00'
<i>a</i> 100	90 00	90 00	0°00'	90 00	86 07	0 00
<i>J</i> 180	28 01½	90 00	0 00	28 01½	88 10½	61 58½
<i>L</i> 160	35 21½	90 00	0 00	35 21½	87 45	54 38½
<i>M</i> 150	40 25	90 00	0 00	40 25	87 29	49 35
<i>Q</i> 130	54 50	90 00	0 00	54 50	86 50	35 10
<i>S</i> 120	64 50½	90 00	0 00	64 50½	86 29	25 09½
<i>n</i> : 101	90 00	33 32	56 28	90 00	29 39	56 28
<i>q</i> : $\bar{1}01$	—90 00	27 47	117 47	90 00	31 40	117 47
<i>s</i> : 301	—90 00	59 46½	149 46½	90 00	63 39½	149 46½
<i>U</i> 123	70 43	15 45	75 05½	84 51½	13 59	75 09½
<i>W</i> 163	43 37	21 06	75 05½	74 53½	19 51	75 37
<i>p</i> 111	78 06	34 06½	56 28	83 21½	30 19	56 43½
<i>i</i> 141	49 51½	40 55	56 28	65 01½	38 01	59 57
<i>l</i> 161	38 20	46 54	56 28	55 03½	44 34	63 04½
<i>n</i> 181	30 40	52 25	56 28	47 01½	50 31	66 09½
<i>z</i> 1.12.1	21 34	60 59	56 28	35 35½	59 37	71 15
<i>e</i> $\bar{1}21$	—62 04	30 48½	117 47	76 07	34 17	116 54½
<i>u</i> $\bar{1}41$	—43 19	37 31½	117 47	63 41½	40 16½	114 42
<i>λ</i> $\bar{1}61$	—32 09	44 43	117 47	53 26½	46 52½	111 59½
<i>v</i> $\bar{1}81$	—25 14½	51 01	117 47	45 19½	52 45½	109 21½
<i>ρ</i> $\bar{1}.10.1$	—20 40	56 11	117 47	38 58½	57 38	107 03
<i>τ</i> $\bar{1}.12.1$	—17 27	60 21½	117 47	33 59½	61 35½	105 06½

STRUCTURAL LATTICE OF JORDANITE

by W. E. RICHMOND

The structural lattice was determined from rotation and zero-layer Weissenberg photographs about the axis [010]. The lattice constants computed from the *x*-ray photographs are:

$$a_0=7.529\text{\AA}, b_0=31.87\text{\AA}, c_0=4.421\text{\AA}; \quad \beta=93^\circ59'$$

giving the axial ratio:

$$a_0:b_0:c_0=0.2362:1:0.1387; \beta=93^\circ 59'$$

in close agreement with the morphological ratio:

$$a:b:c=0.2354:1:0.1397; \beta=93^\circ 53'$$

The volume of the unit cell, V_0 , is 1058.1 cubic Ångströms; with the specific gravity 6.413 (Jackson) this gives a molecular weight for the unit cell of $M_0=4103.2$; with specific gravity 6.32 (new determination) $M_0=4053$.

Using the analysis of Jackson (Solly, 1900), we obtain the figures of Table 2 for the probable content of the unit cell.

TABLE 2. ANALYSIS OF JORDANITE

	1	2	3	4	5	6
Pb	68.61	69.22	.334	13.78	13.53	14 or 13
S	18.19	18.36	.577	23.67	23.38	24 or 23
As	12.32	12.42	.166	6.81	6.73	7
	99.12	100.00				

1. Jordanite from Binn. Jackson, analyst.
2. Recalculated to 100%.
3. Atomic proportions of 2.
4. Atomic content of unit cell using $G=6.413$.
5. Atomic content of unit cell using $G=6.32$.
6. Rounded out atomic numbers.

The figures show little choice between the formulae $\text{Pb}_{14}\text{As}_7\text{S}_{24}$ and $\text{Pb}_{13}\text{As}_7\text{S}_{23}$. We are inclined to select the former. Table 3 shows the calculated composition and density of both formulae as well as of the generally accepted one of $\text{Pb}_4\text{As}_2\text{S}_7$.

TABLE 3. CALCULATED COMPOSITION AND DENSITY OF VARIOUS FORMULAE OF JORDANITE

	$\text{Pb}_{14}\text{As}_7\text{S}_{24}$	$\text{Pb}_{13}\text{As}_7\text{S}_{23}$	$\text{Pb}_4\text{As}_2\text{S}_7$
Pb	69.20	68.13	68.90
S	18.34	18.61	18.65
As	12.46	13.26	12.45
	100.00	100.00	100.00
G	6.54	6.17	5.63

Our inclination is to assign to jordanite the formula $\text{Pb}_{14}\text{As}_7\text{S}_{24}$. If, however, the alternative formula were selected, the chemical identity with meneghinite would be preserved and the two minerals would be dimorphous. New chemical work will be needed before the final decision on this matter can be made.

REFERENCE

Solly, R. H. (1900): Jordanite, *Mineral. Mag.*, vol. **12**, p. 290. Analysis by Jackson, same page 289.

DIAPHORITE

Diaphorite was described by Zepharovich in 1871 as an orthorhombic mineral with the same composition as freieslebenite and nothing of importance has been added since the original description. A specimen of diaphorite from Freiberg in the Karabachek collection yielded a wealth of new data and the results of its study are here presented. Eight crystals were measured in all, four from the new specimen and four from older specimens in the Harvard collection. The latter were similar to the type description and one of them was a twin on the recognized law, twin plane $\{120\}$. The crystals from the Karabachek specimen were highly complex in development; one presented one hundred and fourteen faces representing fifty six forms; and by their study more than fifty new forms were added to the twenty four previously known.

On morphological grounds a new fundamental pyramid was selected which was the pyramid $\{114\}$ of Zepharovich and this choice was confirmed by Winchell's x -ray study presented on a later page. The transformation Zepharovich to Palache is $100/010/00\frac{1}{4}$.

New elements were calculated from the measurements of fifty faces of twenty-five forms on eight crystals.

$$a:b:c=0.4953:1:0.1840$$

$$p_0:q_0:r_0=0.3715:0.1840:1$$

This ratio is closely comparable with that of Zepharovich,

$$a:b:\frac{1}{2}c=0.4919:1:0.1838$$

The table following presents the observations made on these crystals in condensed form, the calculated angles being based on the new elements. The known forms were all found with the exception of the following five:—

	ϕ	ρ	
α 1.11.0	$10^{\circ}24'$	$90^{\circ}00'$	
k 5.12.0	40 04	90 00	
q 0.20.3	0 00	$50\ 48\frac{1}{2}$	(probably vicinal to $\{071\}$, a form missing in the series of domes with $\rho=52^{\circ}10\frac{1}{2}'$)
d 141	26 47	39 30	
ζ 241	45 16	46 17	

DIAPHORITE
TABLE OF CALCULATED AND OBSERVED ANGLES

		Calculated		Observed, mean		Range		No. of		
		ϕ	ρ	ϕ	ρ	ϕ	ρ	faces	Crysts.	Qual.
<i>*c</i>	001	0°00'	0°00'	0°00'	0°00'	0°00' - 0°00'	—	3	3	fair
<i>b</i>	010	0 00	90 00	0 06	90 00	0 00 - 0 16	—	6	4	poor
<i>a</i>	100	90 00	90 00	89 50	90 00	89 27 - 90 00	—	7	7	good
<i>*β</i>	170	16 05½	90 00	16 39	90 00	16 08 - 17 10	—	2	2	poor
<i>*γ</i>	160	18 36	90 00	18 36½	90 00	18 25 - 18 48	—	2	2	good
<i>ρ</i>	150	21 59	90 00	22 07	90 00	22 00 - 22 12	—	3	3	fair
<i>*σ</i>	140	26 47	90 00	26 32	90 00	25 55 - 27 10	—	2	2	poor
<i>π</i>	130	33 56	90 00	33 57	90 00	33 45 - 34 08	—	11	5	fair
<i>n</i>	120	45 16	90 00	45 12	90 00	44 43 - 45 34	—	13	8	good
<i>*ε</i>	230	53 23	90 00	53 43	90 00	—	—	1	1	good
<i>m</i>	110	63 39	90 00	63 40	90 00	63 05 - 64 00	—	14	8	good
<i>*χ</i>	320	71 43½	90 00	71 40	90 00	71 30 - 71 49	—	2	1	good
<i>*δ</i>	210	76 05½	90 00	76 27½	90 00	76 25 - 76 30	—	2	2	poor
<i>i</i>	310	80 37½	90 00	81 52	90 00	81 17 - 82 27	—	2	1	poor
<i>*h</i>	011	0 00	10 25½	0 00	9 01	—	—	1	1	fair
<i>u</i>	021	0 00	20 12	0 00	20 18	—	20°00' - 21°00'	8	5	poor
<i>r</i>	041	0 00	36 21	0 00	36 32	—	36 15 - 36 41	6	4	good
<i>v</i>	061	0 00	47 50	0 00	47 36	—	47 32 - 47 42	2	2	fair
<i>w</i>	081	0 00	55 48½	0 00	55 50	—	55 28 - 56 09	12	8	good
<i>*f</i>	0.10.1	0 00	61 28½	0 00	61 28	—	61 15 - 61 43	5	3	fair
<i>*g</i>	0.12.1	0 00	65 38	0 00	65 38½	—	65 15 - 66 47	3	2	fair
<i>*j</i>	0.14.1	0 00	68 47	0 00	68 38	—	—	1	1	good
<i>ψ</i>	201	90 00	36 36½	90 00	36 30½	—	36 11 - 36 47	7	6	good
<i>x</i>	401	90 00	56 03½	90 00	56 07	—	55 52 - 56 15	7	6	good
<i>*A</i>	112	63 39	11 42½	63 57	11 47	63 32 - 64 22	11 34 - 12 00	2	2	poor
<i>i</i>	111	63 39	22 31	63 54	22 34	63 32 - 64 27	22 06 - 23 03	8	4	good
<i>*B</i>	332	63 39	31 52½	63 45	31 43	63 38 - 63 53	31 41 - 31 45	3	2	fair
<i>γ</i>	221	63 39	39 39½	63 37	39 42	63 04 - 64 22	39 28 - 40 02	13	8	good
<i>*C</i>	331	63 39	51 12	63 35½	51 21	63 22 - 63 53	51 00 - 51 53	5	4	fair
<i>*D</i>	441	63 39	58 54½	63 50	58 48	63 47 - 63 53	58 47 - 58 49	2	2	poor
<i>*E</i>	551	63 39	64 14½	63 58	64 11½	63 53 - 64 01	64 00 - 64 41	4	3	poor
<i>*F</i>	133	33 56	12 30½	33 45	12 44	33 10 - 34 20	12 42 - 12 46	2	1	poor
<i>*G</i>	173	16 05	24 04½	16 40	24 27	16 25 - 16 55	24 12 - 24 42	2	2	very good
<i>*H</i>	132	33 56	18 24	33 52	18 34	33 11 - 34 20	18 20 - 18 48	3	2	fair
<i>*J</i>	172	16 05	33 50	16 17½	33 52	15 47 - 16 50	33 43 - 34 05	5	2	fair
<i>*K</i>	192	12 38½	40 19	12 45	40 26½	12 23 - 13 07	40 07 - 40 33	4	2	good
<i>*L</i>	283	26 47	28 47½	26 31	28 46	26 18 - 26 56	28 38 - 28 55	3	3	poor
<i>M</i>	2.22.3	10 24	53 54½	10 00	54 00	—	—	1	1	good
<i>o</i>	131	33 56	33 38½	34 00	33 38	33 55 - 34 03	33 30 - 33 50	4	4	very good
<i>*N</i>	151	21 59	44 46½	22 00	44 39	21 50 - 22 16	44 16 - 44 56	3	2	poor
<i>*O</i>	171	16 05	53 16½	16 04½	53 19	15 40 - 16 50	53 00 - 53 39	8	3	fair
<i>*P</i>	191	12 38½	59 29½	12 38	59 29	12 16 - 12 59	59 20 - 59 26	3	2	good

DIAPHORITE—Continued

		Calculated		Observed, mean		Range		No. of		Qual.
		ϕ	ρ	ϕ	ρ	ϕ	ρ	faces	Crysts.	
*Q	1.11.1	10 24	64 05	10 29	64 07½	10 20–10 38	64 05–64 10	2	2	good
*R	1.13.1	8 49½	67 33	8 35	67 56	8 30–8 40	67 52–68 00	2	2	poor
*S	312	80 37½	29 27½	80 33½	29 57	80 27–80 40	29 35–30 19	2	2	poor
*T	352	50 27½	35 51	50 34	35 48½	50 12–50 56	35 40–35 57	2	2	poor
*U	392	33 56	44 56½	34 03	44 53	34 02–34 05	44 28–45 05	3	3	poor
*V	211	76 05½	37 25½	76 02	37 30	—	—	1	1	poor
*η	251	38 55½	49 47	38 55	49 40	—	—	1	1	poor
*θ	261	33 56	53 04½	33 59½	53 04½	33 38–34 20	52 33–53 18	7	3	good
*ι	281	26 47	58 46	26 46	58 44	26 38–26 50	58 40–58 50	3	2	good
*κ	2.10.1	21 59	63 15	21 58	63 29	21 50–22 16	63 06–63 47	6	3	poor
*λ	2.12.1	18 36	66 46	18 47½	66 37½	18 40–18 48	66 22–66 53	3	2	poor
*μ	2.14.1	16 05	69 32½	16 04	69 25	16 00–16 08	69 00–69 50	2	2	good
ω	311	80 37½	48 28½	80 32½	48 30	80 16–80 43	48 17–48 42	5	4	poor
*ν	351	50 27½	55 19	50 26	55 22	50 12–50 35	55 00–55 42	3	3	fair
*ξ	391	33 56	63 23½	34 07½	63 21	34 02–34 20	62 52–63 45	4	3	good
*τ	3.13.1	24 59	69 14½	24 54	69 07	24 54–25 02	69 00–69 14	2	2	good
*φ	712	85 57	52 30	86 13	52 50	85 55–86 32	52 36–52 57	3	2	poor
z	421	76 05½	56 50½	76 08	56 54	75 50–76 20	56 30–57 00	5	4	very good
*W	431	69 37	57 45	68 40	57 58	68 31–68 50	57 56–58 00	2	2	fair
*X	4.16.1	26 47	73 08	26 56	72 56½	26 46–27 02	72 35–73 18	4	2	poor
*Z	511	84 20½	61 49	84 12	62 05	83 56–84 31	61 55–62 13	3	2	very good
e	531	73 27	62 42	73 30½	62 48½	73 20–73 45	62 30–63 12	12	6	good
*Δ	621	80 37½	66 07½	80 42	66 07	80 34–80 52	66 00–66 15	4	3	very good
*Λ	641	71 43½	66 55½	71 44	67 03	71 40–71 48	66 46–67 20	2	2	good
*Ξ	711	85 57	69 00½	86 08	69 30	86 06–86 09	69 21–69 40	2	2	good
*Σ	731	78 01	69 23	78 01½	69 38½	77 55–78 22	69 30–69 47	3	3	good
*Θ	841	76 05½	71 54½	76 24	72 05	76 21–76 26	71 45–72 19	3	2	fair
*Υ	971	68 56	74 24	68 57	74 32	—	—	1	1	good
*Ω	10.2.1	84 20½	75 00	84 40	75 18	—	—	1	1	very good
*Ψ	16.2.1	86 27½	80 28	86 12	80 26	—	—	1	1	very good

* Denotes new form.

The prism zone is strongly developed and is striated but distinct faces of {100}, {130}, {120}, and {110} are nearly always present. The termination is generally dominated by some or all of the domes {021}, {041}, {081}, {201}, and {401}. The only pyramids commonly present are {221} and {531}. The crystals are minute and the faces are in most cases not sharply outlined. Nevertheless the angles, as shown in the table, are very consistent and the signals were good for such small faces.

X-RAY STUDY OF DIAPHORITE AND FREIESLEBENITE
by HORACE WINCHELL

In order to better establish the relationship between the two minerals diaphorite and freieslebenite, long held to be dimorphous, an x -ray study was undertaken, employing crystals studied goniometrically, and including a discussion of their chemical character in view of the structural results.

Diaphorite. Weissenberg photographs about the b and c axes, on the zero and the first layers were studied, as well as rotation photographs about all three axes, using $\text{Cu}_{\alpha\alpha}$ radiation. The axial lengths as given below were derived from weighted averages in which the higher order values received the greatest weight.

$$a_0 = 15.83 \text{ \AA}, b_0 = 32.23 \text{ \AA}, c_0 = 5.89 \text{ \AA}$$

$$a_0 : b_0 : c_0 = 0.491 : 1 : 0.183$$

This ratio agrees well with the morphological value given above and confirms the choice of the unit form.

The volume of the unit cell, $V_0 = 3007$ cubic Ångstroms, with the mean observed value of the density, 5.97, gives for the molecular weight of the unit cell $M_0 = 10879$.

The following space group criteria were derived from the zero and first layer Weissenberg photographs about the c axis, and the zero layer about the a axis:—

$$\begin{aligned} hkl & \text{ present only for } k \text{ even} \\ h\bar{k}0 & \text{ present only for } h \text{ and } k \text{ even} \\ h0l & \text{ present only for } h \text{ even} \\ 0kl & \text{ present only for } k \text{ even} \end{aligned}$$

which defines the space group as $D_{2h}^{21}(\text{Cmma})$.

There are two authentic analyses of diaphorite, both on material from Příbram.

	1	2	3	4	5	6	7
Cu	0.73	0.011	26.11	23.36	0.216	23.52	23.80
Fe	0.67	0.012					
Ag	23.44	0.217					
Pb	28.67	0.138	15.01	31.56	0.152	16.56	30.48
Sb	26.43	0.217	23.60	25.92	0.213	23.20	26.86
S	20.18	0.629	68.40	18.51	0.578	62.90	18.87
	<hr/> 100.12			<hr/> 99.35			<hr/> 100.01

1. Analysis by Helmhacker, 1864.
2. Atomic ratios.
3. Number of atoms in unit cell calculated from M_0 .
4. Analysis by Moranski, 1878.
5. Atomic ratio.

6. Atoms in unit cell.

7. Calculated composition for $\text{Ag}_3\text{Pb}_2\text{Sb}_3\text{S}_8$.

The mean of the numbers in columns 3 and 6 when rounded out may be taken as 24:16:24:64 or 8 (3:2:3:8) which lead to the formula $\text{Ag}_3\text{Pb}_2\text{Sb}_3\text{S}_8$, with 8 molecules in the unit cell.

Freieslebenite. No new data on the morphology of this mineral were obtained. A single measurable crystal was found on a specimen from Hiendelencina, Spain, which confirmed the published angles. This crystal was used for the x -ray study. Rotation photographs about b and c , and Weissenberg photographs of the zero and first layers about c were obtained. The cell dimensions obtained are:—

$$a_0 = 7.53 \text{ \AA}, b_0 = 12.79 \text{ \AA}, c_0 = 5.88 \text{ \AA}, \beta = 92^\circ 14' \text{ (morphologic)}$$

$$a_0:b_0:c_0 = 0.589:1:0.460$$

$$a:b:c = 0.5871:1:0.9277$$

$$\beta = 92^\circ 14' \text{ (Miller)}$$

It follows that c must be halved and the transformation formula, Miller to Winchell reads $100/010/00\frac{1}{2}$

The volume of the unit cell, $V_0 = 567$ cubic Ångströms; the specific gravity is 6.23 (Payr), 6.20 (Winchell); these values give as the molecular weight of the unit cell, $M_0 = 2145$.

The space group of freieslebenite is derived from the following systematic criteria:—

hkl present in all orders

$h0l$ present only for h even

$0k0$ present only for k even

Assuming that the crystal class is holohedral the space group is $C_{2h}^5(P2_1/n)$.

The only chemical analysis of freieslebenite which is accompanied by a density determination consistent with our data is that of Payr (1860) made on material from Příbram.

	1	2	3
Fe	0.63	0.11	4.83
Ag	23.08	.214	
Pb	30.77	.148	3.11
Sb	27.11	.223	4.78
S	18.41	.574	12.31
	<hr/> 100.00		<hr/> 25.03

1. Analysis by Payr; density 6.23.

2. Atomic ratios.

3. Number of atoms in the unit cell.

The numbers in column 3 approximate a total of 25 atoms and justify the formula $\text{Ag}_3\text{Pb}_2\text{Sb}_3\text{S}_8$, with one molecule in the unit cell.

SUMMARY TABLE

	Diaphorite	Freieslebenite
Formula	$8(\text{Ag}_3\text{Pb}_2\text{Sb}_3\text{S}_8)$	$\text{Ag}_6\text{Pb}_3\text{Sb}_6\text{S}_{12}$
Symmetry	orthorhombic	monoclinic
	a_0 15.83 Å	a_0 7.53 Å
X-ray elements	b_0 32.23 Å	b_0 12.79 Å
	c_0 5.89 Å	c_0 5.88 Å
Axial ratio	$a:b:c = .4953:1:.1840$	$a:b:c = .5871:1:.4638$ $\beta = 92^\circ 14'$
Specific gravity measured	5.90–6.04	6.20–6.23
Specific gravity calculated	5.97	6.27

The crystallographic and other physical properties of the two minerals considered in this study are shown to be in greater contrast than was before evident; the chemical differences are believed to be real and seem to disprove the supposed dimorphism. Need for new analyses on material physically studied is evident before a final decision can be reached.

POTASH ANALCIME AND PSEUDOLEUCITE FROM THE HIGHWOOD MOUNTAINS OF MONTANA

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Cambridge, Mass.*

INTRODUCTION

This paper is based on a field and laboratory study of the igneous rocks of the Highwood Mountains, Montana, carried on by E. S. Larsen, C. S. Hurlbut, Jr., C. H. Burgess, D. T. Griggs, B. F. Buie, and N. A. Haskell, and we have used freely the collections, field and laboratory notes, and other data of our coworkers. We are indebted to them for permitting us to make use of their material and for helpful co-operation in every way. The work was carried on as a project financed by the Shaler Memorial Fund, and we are grateful to the Department of Geology, Harvard University, for generous support from that fund.

In the field numerous collections were made of the rocks of the area, and specimens were collected from the contact-zone and the centers of many of the dikes and laccoliths in order to study the effect of chilling and slow cooling. Several hundred thin sections from carefully collected specimens were examined.

The potash-rich rocks of the Highwood Mountains are distributed over an area more than twenty-five miles across. In the central part there is a pile of volcanic rocks over a thousand feet thick, also a number of stocks and many smaller intrusives. The Cretaceous sediments about the volcanic rocks are intruded by many dikes, sills, and laccoliths.

The volcanic rocks are nearly all dark basaltic rocks consisting of about one half of phenocrysts distributed through a groundmass whose texture ranges from very fine to rather coarse, for volcanic rocks. The chief phenocrysts are pyroxene, olivine, and leucite, analcime or pseudoleucite or their alteration products. Some rocks have phenocrysts of biotite or of a barium sanidine with as much as 5 per cent of BaO. The groundmasses of the rocks are made up of the same minerals as the phenocrysts, but sanidine and biotite are much more abundant. Plagioclase is lacking in the greater part of the rocks but is present in a few. Of the eighty thin sections of volcanic rocks studied, the following percentages of rock types were found:

Rock Types	Percentages
Basalts with fresh leucite.....	5
Basalts with clear analcime.....	24

Basalts with secondary cloudy isotropic alteration products from leucite or analcime	29
Basalts with natrolite and other zeolites from leucite or analcime.....	10
Basalts with pseudoleucite.....	18
Basalts with feldspar as the felsic mineral.....	7
Mafic phonolites.....	3
Other types.....	4

The dike rocks are in great part very similar to the volcanic rocks but some are phonolites, syenites, and alnoites. The central portions of the dikes are rather coarse grained, and among the basaltic rocks few contain fresh leucite or analcime, and most have pseudoleucite. The stocks are in large part shonkinites, with smaller amounts of nepheline syenites, syenites, monzonites, and very rare granite. The laccoliths are chiefly shonkinites with the central parts of nepheline or sodalite syenites.

POTASH ANALCIME

Many of the fresh lavas and a few of the dikes contain abundant phenocrysts of a clear glassy potash analcime which has the form and appearance of leucite, but lacks twinning and has an index of refraction of 1.493. This analcime is present in rocks that are much like those that contain leucite, except for the higher content of soda and water in the analcime rocks. The analcime is clear in the freshest rocks, but in most specimens it is traversed by cracks along which the analcime is cloudy from alteration, and some of the analcime is completely altered to the cloudy material. The analcime occurs chiefly as phenocrysts but in part also in the groundmass. On its borders it shows a small reaction rim that is made up chiefly of orthoclase. This analcime has all the appearance under the microscope of being a fresh primary mineral and it is found only in the freshest rocks—rocks in which the olivine and other minerals show little alteration and which show no zeolites.

An analysis of a sample of this analcime is shown in Table 1, column 1. Analcime formed at low temperatures is in all cases low in potash, and from our knowledge of the isomorphism of Na and K and from the fact that the atomic radii of Na (0.95) and K (1.33) are very different we should expect little isomorphic replacement of one by the other. At high temperatures we find that K and Na can replace each other to a much greater extent, as in the sanidines. The analcime of the Highwood lavas was probably formed at a high temperature, and this tends to confirm the evidence from the thin sections that these clear analcime phenocrysts are primary.

TABLE 1. ANALYSES OF ANALCIME AND PSEUDOLEUCITE

	1	2	3	4	5	6
SiO ₂	51.41	54.90	49.87	42.43	64.39	56.9
TiO ₂	none			none	0.09	0.1
Al ₂ O ₃	23.03	23.30	22.55	30.11	18.81	22.6
Fe ₂ O ₃	1.35	tr	1.51	0.06	0.91	0.6
FeO						
MnO	none					
MgO	0.43	0.70	1.28	none	none	none
CaO	1.19	1.90	2.62	3.24	0.39	1.3
Na ₂ O	8.48	10.40	10.92	9.61	0.98	3.9
K ₂ O	4.48	1.60	2.66	4.97	13.71	10.8
H ₂ O—	0.28	7.50	11.05	9.67	0.45	3.5
H ₂ O+	9.32					
SO ₃		none	tr			
Cl		none	none			
BaO					none	none
SrO					none	none
	99.97	100.30	102.46	100.09	99.73	99.7

1. Analcime. Phenocrysts from an analcime basalt (FBH 169) from the west end of the ridge that is east of the Geyser-Geraldine road and west of Round Butte. F. A. Gonyer, analyst.
- 2 and 3. Analcime, believed by Lindgren to be primary. From a dike in the Highwood Mountains. Analyses by W. H. Melville.
4. Part of pseudoleucite soluble in acid. From headed dike along Geraldine-Geyser road. F. A. Gonyer, analyst.
5. Part of pseudoleucite insoluble in acid. Same pseudoleucite as 4.
6. Whole pseudoleucite crystals. Same pseudoleucite as 4 and 5.

PSEUDOLEUCITE

Description

Most of the pseudoleucite in the rocks of the Highwood Mountains is made up of a mixture of orthoclase and a cloudy, amorphous material. In some of the lavas, especially where altered, and in a very few of the other rocks, natrolite or analcime takes the place of the amorphous material and locally calcite and other alteration products are present. The orthoclase has low indices of refraction ($\alpha = 1.518$, $\beta = 1.523$, $\gamma = 1.525$) and is low in sodium and barium. The clouded amorphous material has the composition of nepheline with water. It is crossed by cracks and has an index of refraction of 1.500. The pseudoleucite phenocrysts range in size from a few millimeters to ten millimeters or more across.

A representative sample, using whole crystals of the pseudoleucite, was picked out from the pseudoleucite-rich rock in the upper part of the

headed dike and the extraneous material was carefully removed. A two-gram portion of this pseudoleucite was treated with acid by F. A. Gonyer and 66.0 per cent was insoluble. The insoluble fraction was examined under the microscope and was found to be at least 98% feldspar, and the chief impurity was undissolved amorphous material. Both the feldspar and the solution containing the dissolved fraction were analyzed according to standard analytical methods with the results shown in Table 1, columns 4, 5, and 6.

The feldspar of the pseudoleucite is a rather pure potash feldspar. The amorphous material yields approximately the formula $2(\text{Na}_2, \text{K}_2, \text{Ca})\text{O} \cdot 2\text{Al}_2\text{O}_3 \cdot 5\text{SiO}_2 \cdot 4\text{H}_2\text{O}$, which is near that of thomsonite, and it might be considered an amorphous thomsonite. No nepheline was found in the pseudoleucite of the Highwood Mountains, but the amorphous material has about the composition of nepheline with water added, and it was probably derived from the hydration of nepheline.

The feldspar of some of the pseudoleucites is in matted, submicroscopic fibers and in others it is in grains a millimeter or more across. In the fine-textured varieties the feldspar grows in from the boundaries of the leucite crystal, and the amorphous material is concentrated in the central part.

There is a strong tendency for the pseudoleucite to be fine grained in rocks that have fine grained groundmasses and coarse textured in rocks that have coarse-textured groundmasses. This is well shown in the many pairs of specimens from the borders and central parts of dikes. In the laccoliths the chilled borders have pseudoleucite phenocrysts with submicroscopic orthoclase; and, as the rock becomes more coarsely grained away from the contact, the pseudoleucite becomes coarser; and, finally, in the main shonkinite it grades into granular material of the shonkinite. In places in the stocks, dikes, and laccoliths all stages in the recrystallization of the pseudoleucite can be seen from very finely crystalline, with sharp outline, to coarse grained rounded patches in which the individual orthoclase crystals merge with those of the groundmass. Here the chief difference between the pseudoleucite and the groundmass is in the lack of femic minerals in the former. Finally, all evidence of the pseudoleucite is lost and the rocks are ordinary granular rocks.

Occurrence

Somewhat more than half the leucite and analcime of the rocks of the area have been replaced by pseudoleucite. In the lavas some of these minerals have been replaced by a cloudy amorphous material that resembles the amorphous part of the pseudoleucite. A small proportion of the rocks still contains leucite or analcime. Pseudoleucite is abundant

in the dikes and lava flows. It is present in the chilled borders of the laccoliths and stocks and can be recognized in some of the coarse grained rocks of the stocks. Some of the best pseudoleucite (analyses 4-6) comes from the headed dike and can be collected from the cuts along the road from Geraldine to Geyser, about 8 miles southwest of Geraldine.

In many of the rocks the leucite or analcime has been completely converted to pseudoleucite, but in some this conversion has taken place only slightly along the margins, leaving most of the crystals as fresh leucite or analcime, or as the cloudy amorphous alteration product. All stages in the conversion have been found. There is little relation between coarseness of texture of the rocks and the extent to which pseudoleucite has replaced the leucite or analcime, as these minerals with little replacement appear to be at least as common in the granular rocks of the stocks as in the dikes and lava flows. In the dikes whose chilled borders and central parts were both studied, the leucite and analcime of the central parts in which the groundmass and the pseudoleucite are relatively coarse grained, show nearly the same amount of replacement by pseudoleucite as do the chilled borders in which the groundmasses and the pseudoleucite are submicroscopic in texture. Where the border of the dike carries leucite or analcime with narrow borders of pseudoleucite, the central part also carries these minerals with a border of pseudoleucite that is of about the same width as or a little broader than that of the contact rock.

Pseudoleucite was found chiefly in the phenocrysts of the porphyritic rocks, but it was found also in the groundmasses of some of them. It is not present in most of the granular rocks, as in the slow crystallization of such rocks it is commonly lost in the course of crystallization. Many, if not most, of the shonkinites and nepheline syenites originally had pseudoleucite, which has become a part of the granular rock. All stages in this recrystallization have been seen from pseudoleucite with submicroscopic texture, to that with granular texture such that the pseudoleucite can be distinguished only as rounded patches that lack dark minerals, and finally to granular rocks. All the stages have been found in sections from the chilled borders to the centers of some of the dikes and laccoliths.

A very curious occurrence of pseudoleucite, and one difficult to explain, is as large scattered leucitohedrons in a contact metamorphosed sandstone next to the headed dike on the small saddle east of the gulch, three-quarters of a mile east of the Geraldine-Geyser road. At this locality there is no visible sharp contact between the fergusonite of the headed dike and the overlying sandstone. In passing from the typical igneous rock to the sandstone the matrix first becomes a feldspathic rock, with some

interstitial quartz, then a quartzite with interstitial orthoclase and some biotite, and about 12 millimeters from the contact it is a hardened sandstone, and beyond that it is but slightly metamorphosed. In passing into the sandstone the pseudoleucites becomes gradually somewhat smaller, fewer in number and less regularly distributed. These well formed pseudoleucite leucitohedrons, as large as 5 millimeters across, are present as much as 10 millimeters from the contact where they are imbedded in a matrix that is made up chiefly of quartz grains with some interstitial orthoclase and a little biotite.

Time of Formation

The following facts point strongly to the conclusion that the pseudoleucite was formed for the most part after the magmas reached their present positions—after the intrusion of the dikes, sills, and stocks, but before complete crystallization of the rocks.

1. In rocks with fine grained groundmasses, such as the chilled borders of dikes, the pseudoleucite is made up of a very finely crystalline aggregate. The pseudomorphs are in well formed leucitohedrons that are sharply separated from the groundmass so that on weathering well formed pseudomorphs can be broken out, while in rocks with coarse grained groundmasses, such as the centers of dikes, the aggregates that make up the pseudoleucite are correspondingly coarsely crystalline.

2. Pseudoleucite is present in the groundmasses of some of the dikes and lavas.

3. The pseudoleucite phenocrysts are commonly as large and abundant in the chilled borders of the dikes as in the centers, but in some dikes pseudoleucite is present in the groundmass of the main part of the dikes but is lacking or in very small grains in the chilled borders.

Origin

The leucite has not all been replaced by pseudoleucite in the Highwood rocks, and there seems to be no relation between the texture of the rocks and the extent to which the leucite has been replaced. Some of the coarsely granular rocks carry leucite with only slight replacement along the margins, and unreplaced leucite is about as common and abundant in the stocks as in the lavas and dikes.

In the chilled borders of the thirteen dikes studied, the leucite is replaced to nearly the same extent as in the centers of the corresponding dikes, although the intergrowths making up the pseudoleucite are much finer textured in the chilled borders than in the centers.

Schairer and Bowen (1935) believe that pseudoleucite is formed by the reaction of the residual liquid on leucite crystals, as is indicated by

the equilibrium diagram shown in Fig. 1, and they call this reaction the pseudoleucite reaction. However, the facts stated in the preceding paragraph show that in the Highwood Mountains magma the pseudoleucite reaction took place even when the rocks were rapidly cooled and that the leucite remaining in some of the rocks cannot be explained as due to failure of the pseudoleucite reaction to go to completion, but rather to the chemical composition of the liquid phase or of the leucite crystals. The presence of typical pseudoleucite in leucitohedrons five millimeters across in the metamorphosed sandstone as much as ten centimeters from the headed dike is difficult to explain by the "pseudoleucite reaction."

Rittmann (1933, p. 43) concluded that the pseudoleucite of Vesuvius was formed by "autopneumatometamorphism." In the Highwood rocks the cloudy isotropic material of the pseudoleucite may have been formed from nepheline, leucite or analcime by such a process, or by some hydrothermal process or even by weathering, but the orthoclase and original nepheline must have been magmatic.

Knight (1906) concluded that leucite crystallized in the intratelluric stage as soda leucite and that, after the entire magma had solidified, the soda leucite changed to pseudoleucite. In the Highwood Mountains most of the leucite formed in the intratelluric stage but, as shown above, the change to pseudoleucite took place during the solidification of the groundmass. Most of our observations could be explained by assuming that the leucite crystallized with variable amounts of soda leucite in solid solution, with some zoned crystals richer in soda in their outer parts, and that the soda leucite unmixed to nepheline and orthoclase, but the potash leucite did not. Any unmixing must have taken place before the rock was completely crystalline and the resulting pseudoleucite was recrystallized and coarsened in texture where the rock cooled slowly. In this later stage there was certainly some reaction, as the coarse pseudoleucite merges with the matrix and even the least replaced leucites show a lacework border of orthoclase replacement.

It is also possible that the "pseudoleucite" is derived from the unmixing of potash analcime.

Some of the evidence favoring the postulate that pseudoleucite is formed by inversion and not by magmatic reaction is:

1. Well formed crystal pseudomorphs of pseudoleucite with sharp boundaries against the groundmass are characteristic of the rapidly cooled rocks.

2. The extent to which the pseudoleucite has been formed does not depend on the rate of cooling, as many of the rocks with fresh leucite crystals are from coarse grained stocks and in the dikes pseudoleucite

has been formed to about the same extent in the very fine grained chilled borders as in the coarse grained centers.

3. In some of the lavas and near the contacts of some of the dikes the groundmass is submicroscopic in texture and the cooling must have been

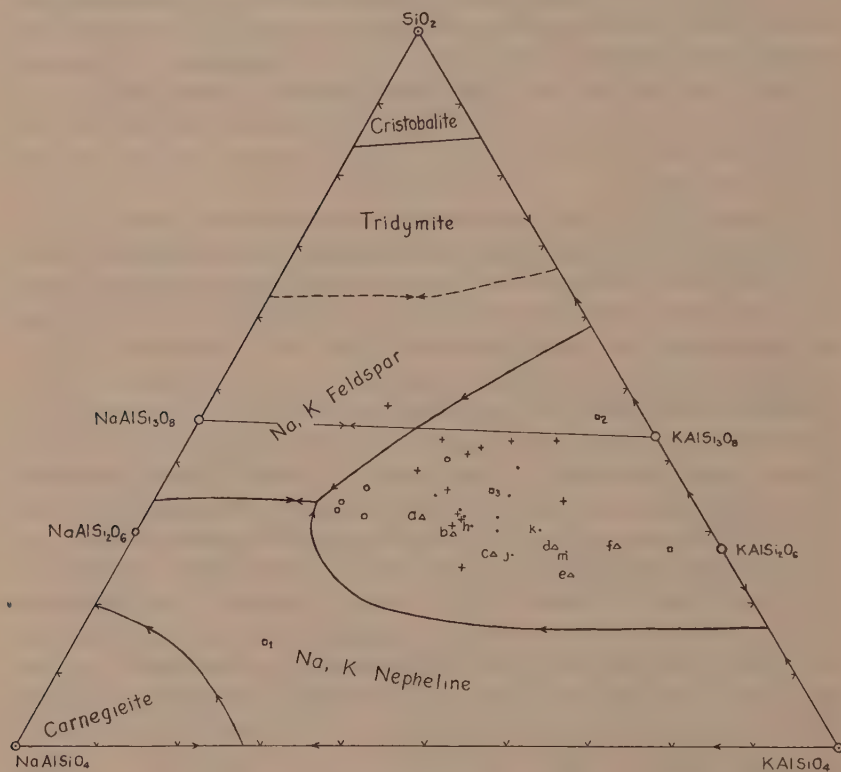


FIG. 1. Equilibrium diagram of the ternary system, $\text{NaAlSiO}_4\text{-KAlSiO}_4\text{-SiO}_2$ (after Schairer and Bowen.), on which the compositions of some Highwood rocks have been plotted.

Dots —Rocks containing pseudoleucite.

Triangles—Rocks containing leucite.

Circles —Rocks containing analcime.

Crosses —Other rock types.

Squares —Pseudoleucite. 1. soluble component; 2. insoluble; 3. soluble and insoluble components.

very rapid, yet in crystals 10 millimeters across the replacement to pseudoleucite is complete. The magmatic reaction on leucite crystals could hardly have been so rapid, requiring, as it does, diffusion both through the leucite crystal and the interstitial liquid. In most of the

rocks the pseudoleucite reaction took place after the magma reached its present position.

Bowen and Ellestad (1937) believe that no soda-rich leucite exists. If such a leucite crystallized from the Highwood magmas, the evidence indicates that unmixing was so rapid that any soda-rich leucite that crystallized from a magma would break down on cooling.

On a preceding page we have shown that analcime with about 4.5 per cent of K_2O is a common phenocryst in the basaltic rocks of the Highwood Mountains. It seems not improbable that an analcime with even more K_2O than $4\frac{1}{2}$ per cent crystallized from some of the basalts and that such analcime rapidly inverted on cooling to "pseudoleucite." The crystal habit of pseudoleucite would be the same whether it was derived from leucite or analcime. Except for the water in the analcime, the chemical compositions of soda leucite and potash analcime would be much the same. The pseudoleucite analysis shown in column 6 of Table 1 yields about the same molecular ratio $(Na, K)_2O$ to Al_2O_3 as leucite or analcime, but it has a little higher SiO_2 content. It has more potash than soda and hence is nearer to leucite than to analcime.

The Highwood rocks offer a favorable opportunity to apply the equilibrium diagram of Schairer and Bowen (1935) for the system nepheline-kaliophilite-silica to a group of rocks, since, except for the barium in the sanidine, the salic part of the rocks can be expressed in terms of these three components. The primary felsic minerals of the rocks are barium sanidine, leucite, nepheline, and perhaps analcime. The normative salic components are therefore plotted on the diagram in Fig. 1. Some of the soda in the normative minerals is in the pyroxene of the mode and some of the potash in the normative minerals is in the biotite of the mode. The six rocks that carry some leucite that has not been replaced by pseudoleucite all fall near the join between leucite and soda leucite. One has as much as four per cent less SiO_2 than the leucites.

The leucite basalt of Pirsson (1905, pp. 168-170) represented by point *a* is altered and of doubtful significance. It was placed among the altered rocks by Washington (1917, p. 921). The other leucite rock rich in soda (*b*) is a leucite shonkinite in which nearly all the original leucite has been replaced by pseudoleucite. The point *c* represents a granular rock from North Peak that contains 35 per cent of leucite that has a little cloudy alteration product and a very little replacement about the periphery by orthoclase. It also contains about 10 per cent of interstitial barium sanidine. The points *d* and *e* represent two analyses of a leucite shonkinite from Shonkin Creek that have from 16 to 50 per cent of leucite and little other felsic minerals. The point *f* represents a leucite basalt from the Bearpaw Mountains. Considering only the rocks that are

clearly leucite rocks, the range in soda content is from 17 to 44 per cent of soda leucite.

The eight analyzed rocks, in which there is pseudoleucite, or good evidence that leucite or analcime first crystallized and was later replaced by orthoclase and nepheline, fall in about the same area of the diagram as do the leucite bearing rocks. They show some less range in the relative proportions of soda and potash, and two of them are richer in silica than are the leucite rocks.

The five rocks that contain analcime that is thought to be primary tend to be slightly higher in silica than the leucite and pseudoleucite rocks. Four of them are richer in soda than the leucite rocks and the other one has a soda content within the range of the leucite and pseudoleucite rocks.

Some of the rocks that show no direct evidence of leucite, analcime, or pseudoleucite fall in or near the field of the leucite and pseudoleucite rocks. Most of these rocks came from the Shonkin Sag and Square Butte laccoliths and in their crystallization leucite probably separated in the early stages and was later so completely reworked that the rocks are now granular nepheline syenites and related rocks. Another part of the rocks that show no evidence of leucite or pseudoleucite, are syenitic rocks and fall near the orthoclase-albite join. There is nothing in these rocks or their field relations to indicate that leucite or analcime formed during their crystallization.

. With the exception of the older quartz latites, which are separated from the younger rocks of the leucite basalt-shonkinite series by an interval of erosion, nearly all the rocks of the Highwood Mountains fall in the leucite field of Schairer and Bowen (1935). The rare quartz syenites are exceptions to this rule.

Assuming that the feldspar and feldspathoid content are those calculated from the norm; that the orthoclase and nepheline in equilibrium with the liquid at the triple point (leucite-orthoclase-nepheline) have the compositions of the insoluble and soluble parts of the pseudoleucite, respectively, as given in Table 1; and that crystallization took place according to the diagram (Fig. 1), most of the leucite- and pseudoleucite-bearing rocks of the Highwood Mountains fall within the triangle nepheline-leucite-orthoclase and in the leucite field. For most of these rocks, leucite would crystallize first, then leucite and nepheline together and finally, at the triple point, nepheline and feldspar would crystallize and leucite be reacted on. Some of the rocks are well within the nepheline-leucite-orthoclase composition triangle, and for these the liquid would be used up before all the leucite was worked over and the resulting rock would be a mixture of orthoclase, nepheline, and leucite. About half of

the rocks fall near the orthoclase-nepheline join, and for these the leucite should be used up at about the same time as the liquid. Three of the pseudoleucite rocks that are rich in silica would crystallize leucite first, then orthoclase with reaction on leucite, then orthoclase and nepheline with reaction on leucite, and finally orthoclase and nepheline after the leucite was completely resorbed.

In this and the following discussion the change in composition during crystallization of the three solid-solution phases is not taken into consideration and equilibrium is assumed.

The pseudoleucite rocks near the orthoclase-nepheline join, and the rock *b* in which most of the original leucite has been replaced by pseudoleucite, followed very nearly the course of crystallization outlined above except that biotite appears to have taken some part in the crystallization.

The leucite rocks lettered *c*, *d*, and *e* and the pseudoleucite rocks lettered *j*, *k*, and *m* followed somewhat different courses. The two rocks, *d* and *e*, are much alike and both came from the Shonkin stock, possibly from the same outcrop. They are 3-millimeter grained rocks and are made up of approximately one-third leucite, much augite, some olivine, one per cent of biotite, and a little iron ore. There is no feldspar or nepheline. The leucite is somewhat clouded, probably from weathering, and an analysis by Pirsson (1905, p. 117) showed 18.86 per cent of K_2O and 0.70 per cent of Na_2O . It is therefore a potash-rich leucite and most of the soda in the rock must be in the pyroxene. The feldspathic part of the rock therefore had the composition of leucite and its crystallization as leucite without reaction fits the equilibrium diagram.

The rock represented by the point *c* on figure 1 is of a type found in five widely scattered small intrusives. It is 3-millimeter grained and contains 20 per cent of leucite, 6 per cent of hyalophane, much pyroxene, and some olivine and ore. The leucite is somewhat clouded from alteration and has been replaced to some extent by orthoclase. The hyalophane is interstitial to the leucite and is strongly zoned. A mixture of 20 parts of leucite and 6 parts of sanidine would form leucite, then orthoclase with reaction on leucite until the whole was crystalline. The actual course of crystallization was much like that postulated from the equilibrium diagram except that much of the feldspar is interstitial and not formed by reaction.

The rock represented by point *b* is much like that of point *c* except that the former rock is a little richer in soda and its leucite has been in large part replaced by pseudoleucite. The rocks represented by points *j* and *m* are from the chilled border of the Shonkin Sag laccolith and have fine grained groundmasses while the rocks represented by points *k* and *h*

are the coarse shonkinites above the chilled border. In all of these rocks the leucite has been completely replaced by pseudoleucite or granular feldspar and nepheline (now altered). These rocks are very similar chemically to the three leucite rocks represented by *c*, *d*, *e*. Why was the leucite replaced in some of the rocks and not in others?

Figure 1 and the preceding discussion show that analcime tends to be in the rocks that are rich in soda and SiO_2 ; leucite is in the rocks with about the amount of SiO_2 to form leucite and with no more soda, molecularly, than potash; pseudoleucite is in rocks with about the same compositions as those of the leucite rocks, although some may contain a little more silica. The rocks without leucite, analcime, or pseudoleucite are for the most part high in silica.

Whether pseudoleucite is formed by unmixing of leucite or analcime or by the pseudoleucite reaction of Bowen (1928) we should expect a more consistent relation between the composition of the rock and the extent of the pseudoleucite replacement than is shown in Table 1.

SUMMARY AND CONCLUSIONS

In the potash-rich province of the Highwood Mountains of Montana, many of the extrusive rocks and some of the dike rocks contain abundant phenocrysts of a clear analcime that appears to be primary. An analysis of the analcime shows $4\frac{1}{2}$ per cent of K_2O , and this high potash content confirms the belief that the analcime is primary.

The rocks of a few of the lavas and stocks, and of a very few of the dikes contain fresh leucite. In the lavas leucite is present both as phenocrysts and in the groundmass. The leucite of the phenocrysts is intratelluric; that of the groundmass crystallized after the magma reached its present position.

Pseudoleucite is an abundant constituent of many of the igneous rocks. It is present also in the metamorphosed sandstone within 10 centimeters from the headed dike. It consists of a mixture of an orthoclase that contains little Na or Ba and an amorphous material that has about the composition of nepheline with water and is probably derived from nepheline.

The extent to which the leucite or analcime has been replaced by pseudoleucite appears to be about as great in the rocks with very fine textured groundmasses, such as the chilled borders of dikes, as in the coarse grained rocks, such as occur in the centers of dikes. The minerals that make up the pseudoleucite tend to be in fine intergrowths in rocks with fine textured groundmasses, and in coarse intergrowths in rocks with coarse textured groundmasses. In the final stage of this coarsening

of the grains of the pseudoleucite the rock becomes an ordinary grained nepheline syenite.

Most of the pseudoleucite formed after the magmas reached their present positions.

The pseudoleucite is formed by the unmixing of either soda-rich leucite or potash-rich analcime. Some of the narrow rims of orthoclase about leucite and analcime were formed by magmatic reaction, and this reaction may have gone farther in some cases.

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